Energy performance of wild-capture marine fisheries at global, regional, and local scales

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Declarations

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Statement of co-authorship

Throughout the four publication chapters in this thesis, the first-person pronoun "we" is used. While this thesis is my own and I was the primary researcher and writer of each chapter, the use of "we" rather than "I" in these chapters reflects the collaborative nature of the research undertaken and the efforts of my co-authors in each project.

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All authors contributed to project formulation and development, survey design, and review and refinement of the manuscript.

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Abstract

Modern wild-capture marine fisheries are underpinned by energy derived from fossil fuels. This energy is required for vessel propulsion and gear operation, onboard processing, freezing and refrigeration, and producing electricity for ancillary services. Fuel use is the primary driver of greenhouse gas (GHG) emissions from marine fisheries, and the second highest cost to fishers globally after labour. Fuel consumption has received increased attention from industry, consumers, governments, and environmental organizations in response to higher and more unpredictable energy prices and the need to reduce GHG emissions to mitigate climate change. A large and growing amount of research has been undertaken since the beginning of the 21st century to measure, characterize, and reduce energy use and GHG emissions in fishing fleets. This thesis provides an overview of the magnitude of fuel consumption in marine wild-capture fisheries, assesses how and why fuel consumption and GHG emissions vary between vessels, fleets, and national industries, and discusses the environmental and economic implications of energy use in fisheries at global, regional, and local scales.

The global-scale research here involved the synthesis and analysis of data pertaining to fuel use in fisheries. Data from all available primary and secondary sources were compiled in a global fisheries and energy use database (FEUD). Observed rates of fuel inputs to global fisheries were characterized by target species, primary gear type, and region. Fuel use rates were then used as a proxy to estimate GHG emissions from national and global fishing fleets, assess the relative emissions from different sectors of the global fishing fleet, and track emissions from the industry from 1990 to 2011. World fisheries in 2011 consumed 40 billion litres of fuel and emitted 168 million

tonnes of carbon dioxide-equivalent GHGs to the atmosphere. Energy performance varied between fisheries by three orders of magnitude, with crustacean fisheries consuming vastly more fuel than fisheries targeting small pelagic forage fish.

Regional-scale research applied cost and revenue data to estimate the fuel use intensity (FUI) of a range of Australian fisheries and compare environmental (emissions) and economic (costs) roles of fuel use. Australian fisheries followed similar patterns to global fisheries, with all of the more fuel-intensive fisheries targeting rock lobsters and prawns, while the more efficient fisheries targeted small pelagics. The economic role of fuel also varied markedly, although fuel costs as a percentage of fishing revenue did not consistently correlate with consumption rates. Fuel expenditures in Australian fisheries ranged from 2% of revenue in abalone fisheries to almost 50% in some prawn fisheries, reflecting not only consumption but also product value. Importantly, some Australian fisheries were identified as having reduced their FUI in recent years: in particular, the Northern Prawn Fishery experienced dramatic improvement in energy performance following substantial management changes including a rapid reduction in number of fishing vessels.

Local-scale research surveyed rock lobster fishers in several locations in Australia and New Zealand to quantify energy performance of different sectors of a single fishing industry (targeting similar species with similar gear and producing similar products), and to determine the relative role of technological, behavioural, and managerial factors in driving fuel use. Average weighted FUI of rock lobster fisheries was 1,890 L/t. Interregional comparisons showed that fuel consumption was lowest in Western Australia and New Zealand, where catch per unit effort (CPUE) was highest. The drivers of fuel use varied between single day and multiday trips—management-related factors, particularly CPUE, were more influential in single day trips, while technological variables played a larger role in multiday trips.

This thesis demonstrates that fisheries vary markedly in fuel use and GHG emissions. Globally and regionally, fuel use largely reflects the species being targeted and the gear being used. Within fisheries, fuel use is influenced by a range of factors, and the relative effect of these factors varies between fishery. It is therefore difficult to generalize across the entire industry when assessing the economic and environmental performance of fisheries and their products in relation to energy use and GHG emissions. Many fisheries can produce low-carbon, climate-friendly sources of animal protein and should be promoted as such, while others are as intensive as high-impact ruminant production. Importantly, more efficient fisheries are not necessarily more resilient to fuel costs, and the economic impacts on these fisheries needs to be considered when discussing subsidies and carbon-pricing policies.

The measurement and characterization of fuel use contributes to our understanding of both the environmental sustainability of fisheries and the economic resilience of fisheries to rising and volatile energy prices and carbon-related policies. Energy resource use and climate change will be defining challenges of the 21st century, and the measurement, characterization, and improvement of energy performance in fishing fleets is required to ensure the socio-economic resilience and environmental sustainability of the industry. Incorporation of these issues into fisheries management and assessments can benefit the industry in the long-term, and help provide a growing global population with affordable, sustainable products from the ocean.

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Acronyms, abbreviations, initialisms, and units

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
CFC	Chlorofluorocarbon
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide-equivalent greenhouse gases
CPUE	Catch per unit effort
CW	Commonwealth of Australia
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FEUD	Fisheries and Energy Use Database
FUI	Fuel use intensity
GHG	Greenhouse gas
GVP	Gross value of production
HP	Horsepower
IMAS	Institute for Marine and Antarctic Studies
ISO	International Organization for Standardization
kg	Kilogram
km	Kilometre
L/hr	Litres per hour
L/t	Litres per tonne
LCA	Life cycle assessment
m	Metre
mg/HP/hr	Milligrams per unit horsepower per hour
N_2O	Nitrous oxide
NPF	Northern Prawn Fishery
NSW	New South Wales
SA	South Australia
SFC	Specific fuel consumption
SO_2	Sulfur dioxide
SRL	Southern rock lobster
t	Metric tonne
TACC	Total allowable commercial catch
TAS	Tasmania
TRL	Tropical rock lobster

Chapter 1. Introduction

Marine capture fisheries are a major source of protein and nutrition around the world and contribute to the socio-economic wellbeing of individuals, communities, and countries (FAO, 2013b). They are also inextricably linked to natural ecosystems and associated with a broad range of environmental concerns, from resource depletion and bycatch of non-target species to destruction of habitat and pollution of marine environments. The concept of sustainability in marine fisheries has developed and expanded beyond assessment of individual fish stocks to include broader environmental considerations and, increasingly, economic and social issues.

While marine fisheries date back many thousands of years, the issues of energy use and greenhouse gas (GHG) emissions are relatively new. Fuel consumption is no longer just an expense to the fishing industry, or a source of pollution, but is now a major threat to climate stability. Even in the context of modern fisheries assessment and management, these issues have only recently received any attention. These issues are of increasing concern in the 21st century, with predictions that peak oil production has already passed or will soon (Murphy and Hall, 2011), and heightened demand for climate change mitigation though emission reductions. Energy underpins almost every element of a fishery, and the industry is heavily reliant on the input of fossil fuels to operate (Tyedmers, 2004; Tyedmers *et al.*, 2005).

This thesis explores the issue of fuel consumption in wild capture fisheries from multiple perspectives and using multiple methods, and assesses the current state of global knowledge on the topic. The work undertaken here is intended to synthesize and assess the published literature on the issue to date, to contribute new findings from case studies in Australia, and to help inform and guide research on measuring, characterizing, and improving the energy performance of marine capture fisheries in the future.

1.1 Global Context

As of 2015, the global population is 7.3 billion people, and it is expected to reach nearly 10 billion by 2050 (United Nations, 2015b). The ability of the world's ecological services to sustain the demands of a large and increasingly affluent population has already been exceeded: 1.5 Earths would hypothetically be required to provide the resources and waste disposal services demanded by even today's population (McLellan *et al.*, 2014). Meeting the needs of a growing population for essential services like food, while also striving to alleviate poverty and provide economic opportunities, presents a myriad of challenges that must be faced over the coming decades. These challenges are further compounded by the limited nature of environmental resources and services and the need to mitigate, and adapt to the effects of, climate change. Marine capture fisheries will need to play a role in meeting the social, economic, and nutritional needs of the world's population, while adapting to new economic and environmental realities.

1.1.1 Climate change and energy

Climate change is the most pressing environmental challenge of the 21st century (Beaumert *et al.*, 2005; Cook *et al.*, 2013; Smith *et al.*, 2013; Peters *et al.*, 2013). Emissions of carbon dioxide (CO_2) and other GHGs have increased dramatically over the past century as a direct result of burning fossil fuels for energy. Atmospheric concentrations of CO_2 have increased by approximately 40% since the beginning of the industrial revolution (Smith *et al.*, 2013). In order to avoid catastrophic climate change and irreversible damage to ecological systems, warming needs to be limited to two degrees Celsius (Smith *et al.*, 2013). This requires a substantial and sustained reduction in global emissions of GHGs. Successfully limiting warming to two degrees, however, seems increasingly unlikely and requires a dramatic shift away from fossil fuels (Peters *et al.*, 2013).

Food production systems account for between 15 and 30% of global GHG emissions (Table 1.1). Production of animal protein, primarily from land-based farming systems, makes up a large share of food-related emissions, alone accounting for upwards of 15-25% of global GHGs. In addition to their associated CO_2 emissions, agriculture and livestock production are the primary sources of anthropogenic emissions of methane (CH_4) and nitrous oxide (N_2O), the second and third most important contributing gases to global warming, respectively (Garnett, 2009; Steinfeld *et al.*, 2006). There is growing evidence that the most effective approach to decreasing emissions from the food sector is through dietary shifts: identifying and limiting production from the most carbon-intensive food systems and replacing them with more sustainable alternatives (Carlsson-Kanyama, 1998; Garnett, 2011; Kearney, 2010; Tilman and Clark, 2014).

Coupled with the environmental challenge of climate change is the reality of limited supplies of, and increasing demand for, oil. Growth in global production of crude oil flattened after 2005, and estimated dates of peak oil range from the early to mid 21st century (Bartlett, 2000; Murphy and Hall, 2011; Murray and King, 2012). Average annual oil prices rose by 330% from 2001 to 2008, peaking at US$145 dollars per

Table 1.1 Estimates of greenhouse gas emissions from food production, as a percentage of global emissions.

Sector	%	Reference
Agriculture and livestock	15	Beaumert *et al.* (2005)
Livestock (exc. land use change)	14	Steinfeld *et al.* (2006)
Livestock (inc. land use change)	18	Steinfeld *et al.* (2006)
Food industry (E.U. only)	31	European Commission (2006)
Agriculture and livestock (exc. land use change)	10-12	Smith *et al.* (2007)
Agriculture and livestock (inc. land use change)	30	Bellarby *et al.* (2008)
Livestock	15-24	Fiala (2008)
Agriculture and livestock	14	World Resources Institute (2009)
Agriculture, livestock, forestry and land use change	24	Smith *et al.* (2014)

barrel during the global financial crisis (EIA, 2015). After 2010, oil prices remained close to or over $100 per barrel. Prices have since declined, but it is likely in the long term that limited supplies and increasing demand will result in continued price increases, while regional interruptions to supply and geopolitical dynamics will keep energy prices highly volatile.

The economic impact of high and unpredictable oil prices is more likely to be felt by fisheries than by many other food production systems, because of the unequivocal role that fuel plays in vessel operating costs around the world and the relatively small response in fish prices as energy costs have risen (Tveteras *et al.*, 2012). Tyedmers *et al.* (2005) estimated that the world's fishing fleets consumed nearly 50 billion litres of fuel in 2000. Fuel is the next biggest cost to fishing companies globally after labour, and is higher in developing countries than in industrialized countries (FAO, 2007). Globally, approximately one-fifth of fishing costs are attributed to fuel, with the relative role of fuel being smallest in Europe and Oceania and greatest in Africa and Latin America (Lam *et al.*, 2011). The impact of high oil prices was demonstrated during the global financial crisis, when entire fishing fleets were forced to cease operations as a result of excessive energy prices (AFP, 2008). Importantly, fuel subsidies to fishing vessels are common and often excessive, particularly throughout fleets from industrialized countries, meaning the true cost of energy to fisheries is even greater than that currently experienced (Sumaila *et al.*, 2010; Sumaila *et al.*, 2008).

1.1.2 Food security

Food security refers to the availability and access to safe, reliable nutrition to sustain a healthy lifestyle (FAO, 1996). One of the United Nations' Millennium Development Goals, to address global issues of poverty, hunger, health, and inequality, was to halve the proportion of the global population living in hunger by 2015. This goal was nearly reached, as the percentage of food insecure people has dropped from 18.7% in 1990-92 to 11.3% in 2015 (United Nations, 2015a). Still, 800 million people worldwide are food insecure, mostly in developing countries in Africa and Asia (FAO, 2014).

Fisheries and aquaculture play a critical role in the provision of protein and essential nutrition to the growing global population, and particularly to the poorest, most impoverished nations. The World Summit on Sustainable Development recognized the importance of marine fisheries in feeding a growing world, calling for the rebuilding of stocks to allow for maximum yields "not later than 2015" (FAO, 1996). Fish is promoted in developed countries as a source of healthy, high-quality protein rich in omega-3 fatty acids and associated with decreased rates of heart disease and other conditions (Beveridge *et al.*, 2013; Sharpless and Evans, 2013). In developing countries, fish provide essential nutrition to reduce malnourishment and provide income for ocean-based economies, and are key for the existence of many poor, subsistence fishing communities (Allison, 2011). In addition to improving food availability, production of fish in local communities improves access to food by avoiding trade barriers and import prices, and participation of individuals in local fishing industries further improves access by providing expendable income (Beveridge *et al.*, 2013).

Table 1.2. Countries which rely on fisheries for more than 50% of their animal protein, showing the proportion of their population that is undernourished.

Country	**fish as % animal protein**[a]	**% of population undernourished**[b]
Maldives	72	6
Sierra Leone	67	26
Cambodia	63	16
Kiribati	60	< 5
Solomon Islands	58	13
Bangladesh	56	17
Sri Lanka	56	25
Indonesia	54	9
Ghana	52	< 5.0
Global	16	12

[a]Calculated from 2011 data(FAO, 2015)
[b]Country-specific data from 2013 (World Bank, 2015), global data from 2013 (FAO, 2013b)

The importance of seafood to food security in the developing world cannot be overstated. Of the 20 countries where seafood accounts for the highest portion of animal protein, 19 are developing countries, and nine of these derive over half of their animal protein from fish and shellfish (Table 1.2). Japan is the most fisheries-dependent developed country, with 38% of their animal protein coming from seafood (FAO, 2015). Developing coastal and island countries not only rely most heavily on fisheries as a source of food and income, but are also most vulnerable to economic impacts on their fisheries as a result of climate change (Allison *et al.*, 2009). Increasing costs of energy are expected to have the greatest effect on fisheries in these same countries, threatening availability of fish protein, direct and indirect income, and the sustainability of local communities with ocean-based economies (Pelletier *et al.*, 2014). Even in developed countries, the poorest households are most susceptible to any increased price in fish as a result of higher input costs (Beveridge *et al.*, 2013).

1.1.3 Fisheries sustainability

Fisheries sustainability is a continuously evolving concept. Traditionally, assessments of fisheries have focused on the status of individual fish stocks (Begg *et al.*, 1999; Larkin, 1978). More recently, fisheries management has expanded to include wider impacts on ecosystems, including non-target species and habitats, following the understanding that managing entire ecosystems is more effective than managing their individual components (Garcia and Cochrane, 2005; Pikitch *et al.*, 2004). Fisheries sustainability is now further expanding to include not only managing stocks and ecosystems, but also managing people; this reflects the need for sustainability to encompass socio-economic elements as well as ecological. In this context, the potential impacts of rising energy costs on communities in both developed (Abernethy *et al.*, 2010) and developing (Pelletier *et al.*, 2014) countries needs to be understood. It can be expected that extreme volatility in the price of oil, and the inevitably higher costs of energy as resources are depleted, could have as much of an economic impact on many fisheries as biomass depletion has had historically. It is necessary to understand the extent of fuel use and emissions in different sectors of the industry in order to assess and improve the adaptability of the industry not only to energy prices directly, but also to carbon-pricing policies and demands by consumers for low-carbon products.

Interest in incorporating energy use and GHG emissions within the concept of fisheries sustainability has come from academia, industry, international fisheries governance, environmental labeling bodies, and non-governmental environmental organizations. The *Code of Conduct for Responsible Fisheries*, a voluntary set of principles and goals developed under the leadership of the FAO to improve the legal framework, management, and conservation of fisheries, explicitly states that:

> *States should promote the development of appropriate standards and guidelines which would lead to the more efficient use of energy in harvesting and post-harvest activities within the fisheries sector* (FAO, 1995, section 8.6).

More recently, there have been calls for the consideration of energy use and GHG emissions in environmental assessments of fishery products and applications of environmental declarations and labels (Madin and Macreadie, 2015; Pelletier and Tyedmers, 2008; Thrane *et al.*, 2009). Seafood Watch, a consumer-oriented seafood sustainability organization at the Monterey Bay Aquarium in the United States, is currently developing energy and emissions criteria for fishery- and aquaculture-derived products (Seafood Watch, 2014). The KRAV food ecolabel in Sweden requires measurement of fuel consumption by fishing vessels and also limits the type of fuel permitted based on sulfur content (KRAV Association, 2015). Sea Fish Industry Authority in the UK has developed tools for industry members to estimate the emissions of their supply chains (Sea Fish Industry Authority, 2015). Some countries, including New Zealand and Norway, have also included fisheries in emissions trading frameworks or applied carbon taxes to fishing operations (Bullock, 2012; Jafarzadeh *et al.*, 2012). As fossil fuel energy resources are depleted, oil prices rise, and national and international initiatives to curb carbon emissions develop, it can be expected that the energy and emissions profiles of marine fisheries will receive more attention.

1.2 Previous research

Analyses of energy inputs to food production systems date back to at least the period following the oil shocks of the 1970s (Leach, 1975; Rawitscher, 1978). Throughout the 1980s and 1990s, very little attention was paid to the energy performance of the fishing industry apart from potential efficiency improvements from engineering innovations (Gulbrandsen, 1986; Wilson, 1999). This reflects the relatively low and stable price of oil experienced throughout the period. Some early analysis of energy inputs to fisheries was undertaken, including to Japanese fisheries and tuna vessels (Pintz, 1989; Watanabe and Okubo, 1989). As a result of the increasing concern regarding climate change and GHG emissions, a large body of literature has been published this century examining fuel use and emissions in fisheries, aquaculture, and other food systems (Parker, 2012b; Roy *et al.*, 2009; Sonesson *et al.*, 2010). Most assessments of fisheries have focused on individual fleets and products (Hospido and Tyedmers, 2005; Ziegler *et al.*, 2003), while some have assessed the performance of regional or global sectors.

Regional assessments of fuel inputs to subsets of national and regional fishing fleets have been undertaken, using various methods, in the North Atlantic (Tyedmers, 2001), Denmark (Thrane, 2004), Norway (Schau *et al.*, 2009), the northeastern United States (Kitts *et al.*, 2008), New Zealand (Hilborn and Tellier, 2012), Japan (Watanabe and Okubo, 1989), India (Vivekanandan *et al.*, 2013), and Taiwan (Hua and Wu, 2011). Tyedmers *et al.* (2005) previously synthesized fuel use data to approximate global fuel consumption for the year 2000; they estimated that the global industry burned just under 50 billion litres of fuel and emitted GHG emissions similar to the total emissions of the Netherlands. On average, this translated to 620 L of fuel for every tonne of fish and invertebrates landed.

Since 2003, a growing body of literature on energy use and GHG emissions in fisheries has come from the application of life cycle assessment (LCA), a framework for quantifying the environmental impacts of a product’s supply chain “from cradle to grave”. Developed as a formal biophysical accounting tool in the 1990s and standardized by the International Organization for Standardization (ISO, 2006), it has been applied to a wide range of marine fisheries production systems (Table 1.3). LCAs of wild capture fisheries have consistently identified the fishing stage—those activities that take place up to the point of landing—as the primary driver of overall impact. Within the fishing stage, fuel consumption to power vessel propulsion, gear operation, and onboard electricity generation is the primary source of emissions (Avadí and Fréon, 2013; Hospido and Tyedmers, 2005; Ziegler *et al.*, submitted). Cases where fuel use does not present the major source of emissions include: artisanal fisheries or other fisheries that consume very low volumes of fuel (Ziegler *et al.*, 2011), products with high-impact agricultural inputs such as oil for canning (Buchspies *et al.*, 2011), or products that are transported by air freight (Driscoll *et al.*, 2015; van Putten *et al.*, *in press*). The extent of LCA application to seafood supply chains has been reviewed by Parker (2012b), Vázquez-Rowe *et al.* (2012a), Avadí and Fréon (2013), and Henriksson *et al.* (2013), and has prompted the development of a seafood-specific method standard (BSI, 2012).

Fuel use in fisheries can be assessed using a variety of methods. Surveying fishermen and fishing companies to solicit fuel consumption and landings data is the most direct approach, and has been employed by several fuel consumption studies (Hua and Wu, 2011; Parker *et al.*, 2015b). Collecting fuel and landings information indirectly from secondary sources, such as government databases, has also been undertaken in countries where fisheries data are regularly collected, particularly in Scandinavia (Schau *et al.*, 2009; Thrane, 2004). Direct and indirect surveys of fishers are the most reliable methods to estimate energy performance and emissions associated fisheries, and are often applied in the undertaking of fishery LCAs. However, if fuel consumption data are not available directly or indirectly, several proxies may provide reasonable estimates of consumption. If average fuel prices and subsidies are known, fuel cost data can be used to calculate consumption (Schau *et al.*, 2009). Vessel effort (days at sea) and horsepower have also been used to calculate fuel consumption in

Table 1.3. Summary of published life cycle assessments of marine capture fishery supply chains and products.

Species	Fishing gear	Fishing location	References
Atlantic cod (*Gadus morhua*)	Trawls; longlines; gillnets	Northeast Atlantic; Denmark; Iceland; Norway; Sweden	Buchspies *et al.* (2011); Ellingsen and Aanondsen (2006); Eyjólfsdóttir *et al.* (2003); Fulton (2010); Guttormsdóttir (2009); Svanes *et al.* (2011); Ziegler *et al.* (2003)
Skipjack tuna (*Katsuwonus pelamis*) and yellowfin tuna (*Thunnus albacares*)	Purse seine	Global	Avadí *et al.* (2015); Hospido and Tyedmers (2005); Parker *et al.* (2015b)
Flatfish	Mixed	Denmark	Thrane (2006)
Norway lobster (*Nephrops norvegicus*)	Traps	Sweden	Ziegler and Valentinsson (2008)
Atlantic horse mackerel (*Trachurus trachurus*)	Purse seine; trawls	Spain	Vázquez-Rowe *et al.* (2010)
Alaska pollock (*Gadus chalcogrammus*)	Trawls	U.S.A.	Fulton (2010)
Pink salmon (*Onchorynchus gorbuscha*)	Purse seine	Canada	Fulton (2010)
Southern pink shrimp (*Penaeus notialis*)	Trawls; artisanal gears	Senegal	Ziegler *et al.* (2011)
Atlantic herring (*Clupea harengus*)	Trawls	Northeast Atlantic; Denmark	Buchspies *et al.* (2011)
Atlantic mackerel (*Scomber scombrus*)	Purse seine; trawls	Northeast Atlantic; Denmark; Spain	Buchspies *et al.* (2011); Ramos *et al.* (2011)
European hake (*Merluccius merluccius*)	Trawls; longlines	Spain	Vázquez-Rowe *et al.* (2011)
Common octopus (*Octopus vulgaris*)	Trawls	Mauritania	Vázquez-Rowe *et al.* (2012b)
European pilchard (*Sardina pilchardus*)	Purse seine	Portugal	Almeida *et al.* (2013)
Goose barnacle (*Pollicipes pollicipes*)	Manual collection	Spain	Vázquez-Rowe *et al.* (2013)
Antarctic krill (*Euphausia superba*)	Trawls	Southern Ocean	Parker and Tyedmers (2013)
Peruvian anchovy (*Engraulis ringens*)	Purse seine	Peru	Avadí *et al.* (2014)
Southern rock lobster (*Jasus edwardsii*)	Traps	Australia	Farmery *et al.* (2014); van Putten *et al.* (*in press*)
American lobster (*Homarus americanus*)	Traps	Canada; USA	Driscoll *et al.* (2015)
Tropical rock lobster (*Panulirus ornatus*)	Diving	Australia	van Putten *et al.* (*in press*)
Prawns (*Penaeus* spp., *Fenneropenaeus* spp.)	Trawls	Australia	Farmery *et al.* (2015)

cases where a gear-specific relationship between effort and fuel use has been established (Tyedmers, 2001). Finally, in cases where specific quantified values are not necessary, broad comparisons have been made based on common patterns in the literature; the KRAV ecolabel in Sweden, for example, used generalized values to indicate expected energy performance of different gear types (KRAV Association, 2015).

1.3 Thesis overview

This thesis consists of four chapters that have been written for individual publication in academic journals. Each paper assesses fuel consumption and GHG emissions in marine capture fisheries, but explores the issue from different perspectives, at different scales, and using different methods. The final discussion summarizes and compares the findings of the four papers, relates the results to the broader context previously introduced, and provides suggestions for future research directions.

1.3.1 Objectives

The goal of this thesis is to provide an overview of the magnitude and implications of fuel consumption in marine wild capture fisheries, and analyze how and why fuel consumption and GHG emissions vary between vessels, fleets, and national industries. The topic is approached from both an environmental perspective and an economic perspective, reflecting the established importance of fuel consumption as both a driver of GHG emissions and a driver of fishing costs. Three scales of analysis are considered: the global scale, to explore variation between national industries and global sectors; the regional scale, using Australia as a case study, to explore variation between fleets; and the local (fishery-specific) scale, using Australian and New

Zealand rock lobster trap fisheries as a case study, to explore variation between vessels. Together, the research undertaken had four objectives:

1) Characterize rates of fuel consumption, and resulting GHG emissions, between fisheries at multiple scales and identify the macro-level factors that drive differences between fleets and industries, including target species, gear, and location;
2) Characterize rates of fuel consumption by vessels within a group of fishing fleets targeting the same type of species and operating the same type of gear, to identify the micro-level factors that drive differences between vessels and fleet subsets, including technology, behaviour, and management;
3) Estimate the contribution of global and regional marine capture fisheries to climate change via GHG emissions up to the point of landing, and discuss the performance of the industry in the context of global food production systems; and
4) Relate the environmental and economic roles of fuel use in fisheries to determine the extent to which emissions and costs can potentially be improved simultaneously through managerial or other efforts, and how the relationship varies between sectors.

1.3.2 Chapters for publication

Chapter Two presents the results of a metaanalysis of the Fisheries and Energy Use Database (FEUD), characterizing fuel inputs to the world's marine capture fisheries by target species group, gear type, and region of fishing. FEUD was originally developed by Dr. Peter Tyedmers at Dalhousie University in Canada, was further populated and developed for analysis purposes by myself beginning in 2010, and is currently co-managed by Dr. Tyedmers and myself. The database, in addition to underpinning the global research undertaken here, has also been used to inform assessments of fisheries by organizations in industry and the non-governmental sector (Parker, 2012a, 2012b). This chapter is intended to introduce FEUD to the academic community, provide an overview of its structure, present descriptive statistics of the current dataset, and discuss potential applications. It was published in *Fish and Fisheries* in 2015.

Chapter Three combines the findings of global fuel inputs reported in Chapter Two with a database of global fishery landings managed by Dr. Reg Watson at IMAS. A hierarchical matching of landing records with fuel use records, according to target species or target species group, gear type, and fishing country, was used to estimate rates of fuel use for all reported landings. Fuel consumption was translated into estimates of GHG emissions, based on established relationships between fuel and emissions from the literature, in order to quantify the contribution of national fleets, as well as the global fishing industry as a whole, to climate change. Results are presented in terms of overall aggregated emissions, emissions intensity per unit of live weight fish landed, and national emissions from fisheries relative to emissions from agriculture and livestock production.

Chapter Four characterizes fuel inputs, fuel-related GHG emissions, and fuel costs for a range of Australian fisheries. Australian fisheries provide a unique opportunity to explore the relative importance of fuel environmentally and economically, as there is a vast variation in the economic characteristics of Australian fisheries, and prices received for products in many of Australia's fisheries far exceed global averages. This chapter estimates fuel inputs based on revenue and cost data for state- and Commonwealth-managed fisheries, and indicates the role of fuel in both the environmental (emissions) and economic (costs) performance of Australian fisheries. It was published in the *Journal of Cleaner Production* in 2015.

Chapter Five assesses variation in fuel consumption between vessels targeting rock lobster species using traps in Australia and New Zealand. Surveys were distributed to fishers in four Australian states (Western Australia, South Australia, Tasmania, and New South Wales) as well as New Zealand. The relative fuel performance of vessels was assessed against a range of variables: technological (vessel length, engine horsepower, engine efficiency, specific fuel consumption), behavioural (trip length, distance to fishing grounds, average speed, perceived importance of fuel by fishers, whether fishers have actively changed operations in response to fuel costs), and managerial (catch per unit effort, number of pots per vessel, number of vessels fishing relative to total quota, number of pots in the fishery relative to total quota). Multiple regression analysis was undertaken to determine the extent to which different factors influence fuel use by rock lobster vessels undertaking single day and multiday trips.

The thesis concludes with a brief overview of the findings presented in each publication chapter and implications for industry, policy, and research. The extent to which fuel use varies between fisheries locally, regionally, and globally is summarized, as well as the common drivers of fuel use between and within fishing fleets. The contributions of the thesis to ongoing efforts to understand the environmental and economic implications of energy use in fisheries are discussed, suggestions are made to improve approaches to future fuel use studies, and potential research directions are posited.

Chapter 2. Fuel consumption of global fishing fleets: Current understanding and knowledge gaps

This chapter was accepted as an article in the journal *Fish and Fisheries* on 5 June, 2014, and published in volume 16, issue 4, in December, 2015 (see Appendix E). It is presented here in its published form, with formatting changes and updated citations where applicable. The research was funded in part by the Australian Seafood Cooperative Research Centre. Names and institutions of contributing authors are:

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2.1 Abstract

Compared to a century ago, the world's fishing fleets are larger and more powerful, are travelling further and are producing higher quality products. These developments come largely at a cost of high fossil fuel energy inputs. Rising energy prices, climate change and consumer demand for 'green' products have placed energy use and emissions among the sustainability criteria of food production systems. We have compiled all available published and unpublished fuel use data for fisheries targeting all species, employing all gears and fishing in all regions of the world into a Fisheries and Energy Use Database (FEUD). Here we present results of our analysis of the relative energy performance of fisheries since 1990 and provide an overview of the current state of knowledge on fuel inputs to diverse fishing fleets. The median fuel

use intensity of global fishery records is 639 litres per tonne. Fuel inputs to fisheries vary by several orders of magnitude, with small pelagic fisheries ranking amongst the world's most efficient forms of animal protein production and crustaceans ranking among the least efficient. Trends in Europe and Australia since the beginning of the 21st century suggest fuel use efficiency is improving, although this has been countered by a more rapid increase in oil prices. Management decisions, technological improvements and behavioural changes can further reduce fuel consumption in the short term, although the most effective improvement to fisheries energy performance will come as a result of rebuilding stocks where they are depressed and reducing over-capacity.

2.2 Introduction

Limited availability of conventional energy sources, rising energy prices, and the need to reverse the trend of climbing greenhouse gas (GHG) emissions are issues that will shape global economic and socio-political dynamics in the first half of the 21st century. The decade from 2003 to 2013 saw oil commodity prices climb by over 300% (EIA, 2012) and it is commonly argued that global oil production has either already peaked or will peak in the near future (Bartlett, 2000; Murphy and Hall, 2011). Meanwhile, global GHG emissions continue to rise, particularly as large developing and transitional economies become more affluent. Food production, and production of animal protein in particular, has been recognized as placing substantial burden on ecological services such as land and water use, and also contributing heavily to national and global GHG inventories (Garnett, 2008; Steinfeld *et al.*, 2006). National and global estimates of GHG contributions from food production range from between 10 and 30% of total emissions (Garnett, 2011).

Marine capture fisheries represent a major source of food, employment and income globally. Fish products—from both wild fisheries and aquaculture—contribute approximately 17% of global animal protein consumption and are a particularly important source of protein, lipids and micronutrients in poor, undernourished countries (FAO, 2013b; Garcia and Rosenberg, 2010). Fisheries contribute to poverty alleviation and food security via provision of food, raising purchasing power through employment, and generation of national revenue through exports, taxes and access fees (Allison, 2011; Garcia and Rosenberg, 2010). Global employment from marine fisheries has been estimated at 260 million jobs, including some 50 million fishers and 210 million employed indirectly in processing, distribution, trade and other services (Teh and Sumaila, 2013). Seafood from fisheries and aquaculture is the most heavily traded food commodity worldwide, with over one third of global fish production flowing into international trade worth over US$100 billion annually (FAO, 2013c; World Bank, 2009). Despite being a highly valuable and nutritionally critical industry, the marine fishing sector is facing multiple challenges including weakened profitability in recent decades, related to increased costs of operation, volatile markets and prices, and depressed fish stocks (World Bank, 2009).

Advances in fishing and processing technology, as well as globalization of trade and markets, have transformed marine fisheries since the mid 20th century. Fisheries today are targeting previously unharvested species, fishing in new regions and depths, particularly in the high seas, producing higher quality products and distributing products around the world in multiple product forms (FAO, 2013; Thorpe *et al.*, 2007). These advancements have increased production, expanded fish markets and improved product quality and fisher safety. A consequence of many of these advancements has been the increased reliance of fisheries on larger vessels, the motorization of fishing fleets with more powerful engines and the increased demand by fisheries for fossil fuels to power everything from propulsion and gear operation to onboard processing, refrigeration, and ancillary services such as navigational aids (Tyedmers, 2004; World Bank, 2009). Global marine fisheries have, in essence, followed a similar trend towards highly productive industrialized operations that agricultural production underwent in the 20th century. As a result of this reliance on energy inputs to modern fishing fleets, primarily in the form of fossil fuels, fisheries and their products are increasingly vulnerable to the cost of fuel, regulations on emissions (*e.g.* carbon taxes), and consumer demands for low-impact, 'green' products.

Expenditures on fuel represent one of the largest costs in modern fishing operations. Globally, between 30 and 50% of fishing expenditure is on fuel, with small scale fisheries and fisheries in developing countries spending a higher proportion on fuel than those in developed countries (FAO, 2012; Lam *et al.*, 2011). The increase in fuel costs over the past decade has easily outpaced the growth in fish prices (Tveteras *et al.*, 2012), culminating in the temporary shutdown of some energy-intensive fisheries during the price peaks of 2008 (AFP, 2008; Kyodo News, 2008). Offsetting fuel costs is also the primary purpose of many subsidies to fisheries worldwide, with particularly high levels of government intervention in richer countries (Sumaila *et al.*, 2008).

Fuel consumption by fishing vessels is typically the dominant driver of energy demand and GHG emissions from fisheries production, accounting for between 60 and 90% of emissions up to the point of landing (Tyedmers, 2004). Additional upstream processes associated with fishing, including vessel construction and maintenance, gear manufacturing, and bait provision, also consume energy and produce emissions. When viewed in the context of total life cycle ("cradle to grave") emissions, including post-landing activities such as processing, packaging, transport and food preparation, vessel fuel use remains a primary source of emissions from seafood supply chains (Parker, 2012b; Vázquez-Rowe *et al.*, 2012a).

Relatively little research was published on fuel consumption in fisheries prior to 2000. Some early analyses of energy inputs to fisheries and other food production systems were completed in the wake of the 1970s oil shocks (Leach, 1975; Rawitscher, 1978; Watanabe and Okubo, 1989). Increasing energy prices and concern related to GHG emissions have sparked renewed interest in the topic, and numerous regional and fishery-specific analyses have been undertaken in the past decade. Tyedmers *et al.* (2005) estimated global fuel use intensity (FUI) at 620 L/t in 2000, or a total industry-wide consumption of 40 billion litres. This value equates to just less than 2 kg of fuel-related GHG emissions per kg of fish caught, before accounting for additional inputs to processing and transportation. A key finding from this set of research was that fisheries, facing relatively low costs of fuel and a growing challenge of over-capacity and declining fish stocks, had been increasing their FUI throughout the 1990s. Furthermore, the extent to which modern fisheries were relying on fuel consumption meant that the energy inputs to many systems far outweighed their energy outputs in terms of edible fish protein.

Since the early 2000s, environmental and economic concerns have resulted in a growing body of research into energy demands and GHG emissions of fisheries, aquaculture, and other food production systems. Energy, fuel and GHG-related research in fisheries in the past decade has included efficiency audits of individual vessels and fleets (Sala *et al.*, 2011; Thomas *et al.*, 2010), assessments of fuel inputs to national or regional fleets (Schau *et al.*, 2009; Thrane, 2004; Tyedmers, 2001), global assessments of fishing sectors (Parker *et al.*, 2015b) and life cycle assessments of fishery-derived products (Avadí and Fréon, 2013; Parker, 2012b).

Here we draw upon this growing field of analyses to provide an overview of the current state of research into energy use in marine capture fisheries. We present the results of an analytical synthesis of primary and secondary FUI data to identify patterns of fuel use in fisheries targeting different species, employing different gears, and operating in different regions. It is our intention that this metaanalysis of energy use in fisheries will provide a broad overview of the status of the issue from both an environmental and an economic perspective and highlight significant gaps in our collective understanding of energy use in fisheries. The insights and discussion presented here should be of interest to those directly engaged in the fishing industry, as well as fisheries managers and regulating bodies, non-governmental agencies, consumers, and LCA practitioners.

2.3 Methods

2.3.1 Fisheries and energy use database

A Fisheries and Energy Use Database (FEUD) was developed by P. Tyedmers in Microsoft Access and is currently maintained by both authors to collect and synthesize primary (unpublished analyses or re-analyses by the authors) and secondary (from published articles or reports) records of FUI of fishing vessels or fleets. Database records include, where available, fleet and/or vessel characteristics (*e.g.* horsepower, gross registered tonnage, *etc.*), target species, locale of fishing, primary and secondary gears employed, effort (*e.g.* fishing days), and FUI. To date, FEUD includes over 1,600 records covering a wide range of fisheries from all regions of the world, employing all major gears, and targeting all major species classes, dating back to 1956 (see Appendix A). Previously, FEUD has been used to estimate fuel inputs to global fisheries in 2000 (Tyedmers *et al.*, 2005).

2.3.2 Fuel use intensity analysis

Records of fisheries FUI were extracted from FEUD and aggregated by species, gear and region. Only data referring to fisheries operating in 1990 onwards were included for analysis here. Analysis of FUI by species excluded all records for which species class was unknown. Likewise, analysis of FUI by gear type excluded records for which gear type was unknown. Records were not weighted based on global catch patterns, as the intention here was rather to assess the FUI data available and identify consistent patterns.

Data were imported to R and summary statistics were generated, including mean, median, quartiles, and maximum and minimum values. This statistical summary was then used to generate graphics and compare the FUI records of fisheries targeting different species, employing different gears, and fishing in different regions.

2.4 Results

2.4.1 Status of database

An overview of the total number of fisheries records currently collected in FEUD is presented in Table 2.1. There is a clear pattern of FUI data being more plentiful for fisheries in Europe and those targeting finfish species. In fact, 146 records pertain to European fisheries for Atlantic cod (*Gadus morhua*) alone. The large number of records from Europe and Oceania is the result of recent robust analyses of FUI in fisheries of those regions, particularly for the North Atlantic (Tyedmers, 2001), Norway (Schau *et al.*, 2009), Denmark (Thrane, 2004), the European Union (Anderson and Guillen, 2011), New Zealand and Australia (Parker *et al.*, 2015a). While some very recent analyses of energy use in Indian and Southeast Asian fisheries have been published (Boopendranath and Hameed, 2013; Hua and Wu, 2011; Vivekanandan *et al.*, 2013), there is a clear lack of fuel use data pertaining to small-scale fisheries in developing countries. African and South American fisheries in particular are grossly underrepresented.

2.4.2 Fuel use intensity by species, gear and region

The unweighted mean FUI of all fisheries fuel use records since 1990 is 706 L/t, and the median FUI of all records since 1990 is 639 L/t. FUI varies considerably between fisheries, on the scale of three orders of magnitude, but several patterns are clear when comparing fisheries on the basis of target species class and primary gear type (Figure 2.1 and Table 2.2).

The most efficient fisheries are those targeting small pelagic species such as Peruvian anchovy (*Engraulis ringens*), Atlantic mackerel (*Scomber scombrus*) and Australian

Table 2.1. Number of records (total and for fisheries operating since 1990) in the Fisheries and Energy Use Database, by species class, gear type, and region.

Fishery Category	**All records**	**Year ≥ 1990**
By species class		
Finfish	512	320
Small pelagics	260	188
Crustaceans	372	303
Molluscs	197	94
Large pelagics	113	91
Flatfish	76	68
Salmonids	24	7
Other/unknown	68	55
By gear type		
Bottom trawls	479	347
Hooks and lines	266	110
Surrounding nets	223	145
Pelagic trawls	174	143
Gillnets	114	68
Pots and traps	83	74
Dredges	62	50
Divers	16	16
Other/unknown	205	173
By region		
Europe	866	640
Oceania	323	303
Asia	224	34
North America	159	115
Africa	24	7
Latin America	2	2
Other/unknown	24	24
Total records	1,622	1,126

sardine (*Sardinops sagax*). These fisheries make up some of the largest in the world, by volume of landings, but are often directed primarily to the production of animal feeds and other products, rather than for direct human consumption. They are particularly efficient when using purse seine gear or other surrounding nets, averaging 71 L/t, while small pelagic fisheries employing pelagic trawls average 169 L/t. The lowest FUI values on record (apart from non-fuel consuming artisanal fisheries) are for fisheries targeting Atlantic herring (*Clupea harengus*) in Iceland (Tyedmers, 2001) and Peruvian anchovy in Chile (P. Trujillo, UBC Fisheries Centre, personal communication); FUI values for these and similar fisheries are typically under 100 L/t, with some reported values as low as 8 and 10 L/t.

The least energy-efficient fisheries globally are those targeting crustaceans, particularly species of shrimps and lobsters, using either bottom trawls or pots and traps. Many of these fisheries have recorded FUI values of up to, and even over, 10,000 L/t. Among the most fuel-intensive fisheries in the world are those targeting Tiger prawns (*Penaeus monodon*, *Penaeus esculentus*) with bottom trawls in Australia, and Norway lobster (*Nephrops norvegicus*) with bottom trawls in Sweden, with reported FUI values higher than 11,000 and 17,000 L/t, respectively. Overall, crustacean fishery records in FEUD have an average value of 2,923 L/t. Other fuel-intensive forms of fishing include flatfish bottom trawls, averaging 2,827 L/t, and large pelagic (primarily tuna) fisheries using longlines and other forms of hooks and lines (*e.g.* trolling), averaging 1,612 L/t.

Variations in FUI between regions are less clear than those between species class and gear type. One evident regional pattern is the relatively high FUI of records from

Table 2.2. Average FUI of fishery records with known target species, gear type, and region, since 1990.

Fishery Category				Fuel Use Intensity (L/t)		
Species class	**Gear type**	**Region**	**n**	**mean**	**min**	**max**
Crustaceans	Bottom trawls	Oceania	88	4,125	1,165	10,886
Crustaceans	Pots and traps	Oceania	53	3,803	846	9,474
Crustaceans	Bottom trawls	Europe	117	3,083	377	17,300
Flatfish	Bottom trawls	Europe	32	2,851	631	4,062
Molluscs	Bottom trawls	Europe	7	2,618	1,205	4,103
Crustaceans	Bottom trawls	Africa	1	2,600	2,600	2,600
Molluscs	Gillnets	Europe	1	2,162	2,162	2,162
Crustaceans	Pelagic trawls	Asia	1	2,028	2,028	2,028
Large pelagics	Hooks and lines	Asia	3	1,925	106	4,985
Large pelagics	Hooks and lines	Europe	12	1,745	570	3,478
Large pelagics	Hooks and lines	Oceania	20	1,676	937	3,300
Large pelagics	Hooks and lines	North America	4	1,495	385	2,678
Finfish	Pelagic trawls	Europe	2	1,444	413	2,475
Crustaceans	Bottom trawls	North America	12	1,231	531	2,262
Molluscs	Pelagic trawls	Oceania	2	1,097	406	1,787
Flatfish	Pelagic trawls	Oceania	4	1,086	918	1,480
Flatfish	Bottom trawls	North America	3	1,084	957	1,338
Crustaceans	Hooks and lines	Europe	2	1,031	47	2,015
Molluscs	Divers	Oceania	16	951	585	1,472
Finfish	Hooks and lines	Europe	42	927	125	4,238
Small pelagics	Bottom trawls	Asia	1	922	922	922
Salmonids	Gillnets	North America	2	886	785	986
Molluscs	Bottom trawls	North America	2	859	313	1,405
Salmonids	Hooks and lines	North America	2	835	735	935
Crustaceans	Pots and traps	Europe	8	834	334	2,156
Large pelagics	Bottom trawls	North America	1	824	824	824
Crustaceans	Pots and traps	North America	3	783	331	1,026
Finfish	Bottom trawls	Asia	3	766	671	874
Finfish	Bottom trawls	Europe	55	756	236	2,724
Large pelagics	Gillnets	Oceania	9	751	397	1,352
Finfish	Gillnets	North America	37	686	300	1,532
Large pelagics	Gillnets	Asia	1	683	683	683
Finfish	Bottom trawls	North America	15	682	65	1,457
Finfish	Pelagic trawls	Oceania	40	675	207	1,495
Crustaceans	Pelagic trawls	Europe	2	634	232	1,035
Crustaceans	Gillnets	Africa	1	630	630	630
Large pelagics	Pelagic trawls	Oceania	6	627	151	1,649
Small pelagics	Gillnets	Europe	1	602	602	602
Flatfish	Gillnets	Europe	1	598	598	598
Flatfish	Hooks and lines	North America	1	570	570	570

Table 2.2 (continued).

Flatfish	Bottom trawls	Asia	1	549	549	549
Finfish	Hooks and lines	Oceania	1	549	549	549
Finfish	Bottom trawls	Oceania	3	538	363	665
Molluscs	Bottom trawls	Oceania	1	533	533	533
Molluscs	Dredges	Europe	44	525	15	1,822
Flatfish	Gillnets	North America	3	517	492	566
Molluscs	Pots and traps	Europe	7	513	392	641
Finfish	Surrounding nets	Europe	13	466	104	659
Large pelagics	Surrounding nets	Europe	3	447	373	527
Finfish	Dredges	North America	1	445	445	445
Finfish	Gillnets	North America	8	443	297	1,430
Small pelagics	Bottom trawls	North America	2	431	230	631
Finfish	Hooks and lines	North America	7	411	396	489
Flatfish	Surrounding nets	North America	1	380	380	380
Finfish	Surrounding nets	Oceania	18	346	62	497
Small pelagics	Hooks and lines	Europe	2	323	60	585
Molluscs	Dredges	North America	5	295	71	361
Salmonids	Surrounding nets	North America	3	291	56	513
Small pelagics	Pelagic trawls	Oceania	7	234	141	354
Finfish	Surrounding nets	North America	1	230	230	230
Large pelagics	Gillnets	North America	1	199	199	199
Large pelagics	Surrounding nets	Oceania	1	195	195	195
Small pelagics	Pelagic trawls	Europe	28	168	45	565
Finfish	Surrounding nets	Asia	1	162	162	162
Large pelagics	Surrounding nets	Asia	2	156	149	162
Small pelagics	Surrounding nets	Asia	2	152	142	162
Crustaceans	Pelagic trawls	North America	1	132	132	132
Small pelagics	Pelagic trawls	North America	6	101	49	147
Small pelagics	Surrounding nets	Oceania	17	89	29	217
Small pelagics	Surrounding nets	Europe	36	84	8	506
Small pelagics	Bottom trawls	Europe	3	83	65	94
Finfish	Pelagic trawls	North America	8	66	36	73
Small pelagics	Surrounding nets	North America	20	42	20	160
Small pelagics	Surrounding nets	Africa	6	31	16	46
Small pelagics	Surrounding nets	Latin America	2	10	10	10

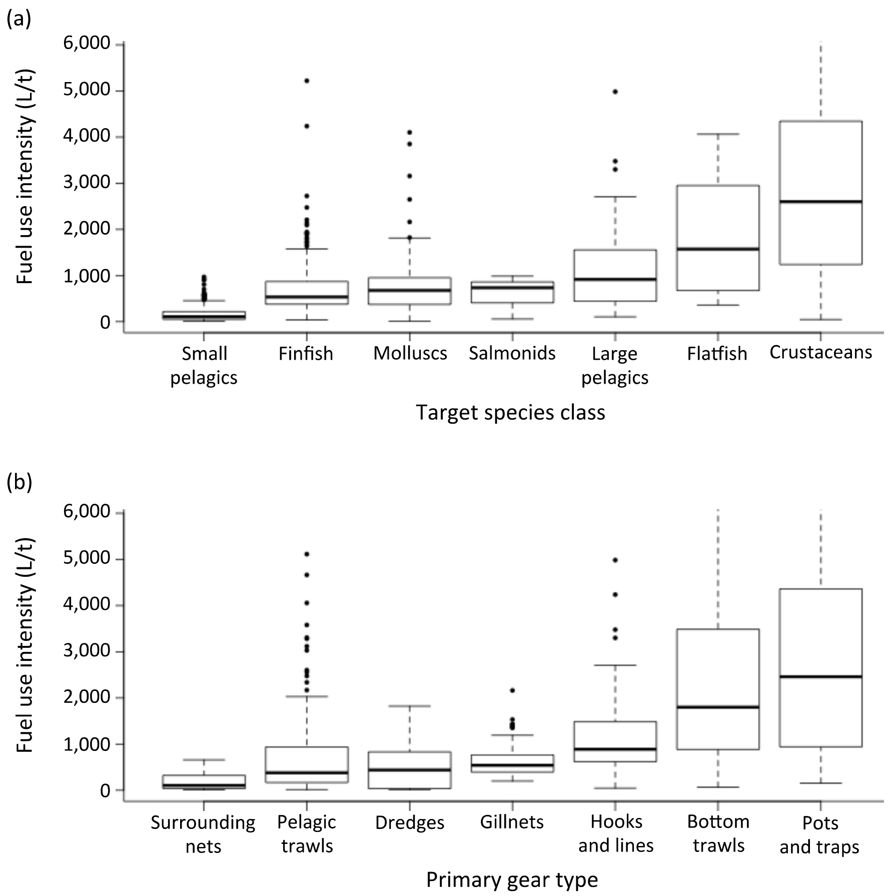

Figure 2.1. Median and range of fishery FUI records by (a) species class and (b) gear type. Boxes represent 25th and 75th percentiles while dots denote outliers. Note that, while the y-axis is truncated at 6,000 L/t for graphical purposes, some FUI values for crustacean fisheries, pots and traps, and bottom trawls, are higher.

Oceania, which have a mean value of 2,183 L/t. This is driven primarily by the high occurrence of fuel-intensive crustacean fisheries in Australia and by the large number of FUI records pertaining to those fisheries. Average FUI values for records from North America (432 L/t) and Europe (859 L/t), meanwhile, are lower as a result of the prevalence of fisheries for finfish and small pelagic species. Regional variations within fishery categories have been reported elsewhere, although inconsistently. Purse seine fisheries for skipjack tuna (*Katsuwonus pelamis*), for example, are reported as more efficient in the Indian Ocean by Hospido and Tyedmers (2005) and more efficient in the Pacific Ocean by Parker *et al.* (2015b) although these apparent differences may be a function of sample size or a genuine change in FUI over time. Fisheries for lobster species vary dramatically between regions, with the difference in fuel consumption between American lobster (*Homarus americanus*) and Norway lobster being a full order of magnitude. Additional regional trends are likely to exist, such as differences in FUI between small-scale fleets using outboard motors and larger vessels with inboard engines in developing countries; however, a lack of publicly available data to date makes these assertions impossible to test.

2.5 Discussion

2.5.1 Comparison to previous findings

This is the first broad global overview and classification of FUI of fisheries relative to species, gear, and region. Results, however, reflect findings of previous national or regional fleet assessments in many ways. The lower fuel demand of small pelagic fisheries has been highlighted previously in analyses of North Atlantic, European, and Australian fisheries (Parker *et al.*, 2015a; Schau *et al.*, 2009; Tyedmers, 2001).

Likewise, the lower FUI of purse seines and surrounding nets has also been demonstrated previously on smaller scales (Schau *et al.*, 2009; Tyedmers, 2001)

Estimates of FUI presented here, while averaged across FUI records and unweighted by relative catch, resemble previous findings for fisheries in fleet- and vessel-specific analyses, suggesting a relative degree of consistency across fuel use studies of different fleets, different regions, or different years. Median FUI for large pelagics caught using hooks and lines (1,485 L/t) and surrounding nets (434 L/t), for example, are close to global tuna FUI assessment findings for 2009 (Parker *et al.*, 2015b; Tyedmers and Parker, 2012). Likewise, the median FUI of finfish fisheries (519 L/t) is very close to the FUI values previously reported for Atlantic cod fisheries in Europe and the North Atlantic, taking into consideration variation between gear types (Svanes *et al.*, 2011; Tyedmers, 2001; Ziegler *et al.*, 2003).

Tyedmers and colleagues (2005) estimated global FUI of fisheries to be 620 L/t for the year 2000. This very closely corresponds to the median value of FUI records of 639 L/t found here. While this is not particularly surprising as both studies analyzed data from FEUD, the current study benefitted from a much larger set of recent data points; the similarity in results, then, reinforces the previous estimate. The mean FUI of records in FEUD, 706 L/t, is positively skewed by high FUI values for crustacean and flatfish fisheries and by a lower FUI truncation at 0 L/t.

2.5.2 Knowledge gaps and need for additional data

It is clear from the data presented here that research into the fuel performance of fisheries has been largely limited to modernized commercial fleets in developed countries, particularly those operating in Europe. There is a stark absence of meaningful data from developing countries, and relatively few assessments have been undertaken on small scale and artisanal fisheries; exceptions include Vivekanandan *et al.* (2013), Ziegler *et al.* (2011) and Boopendranath and Hameed (2013). In fact, while African and Asian fleets account for over 50% of landings by global fisheries (FAO, 2011), they represent only a small fraction of available FUI data. This bias of fuel use data towards developed countries, and particularly European fleets, was previously identified by Tyedmers *et al.* (2005) and by Parker (2012b) in assessing carbon footprint studies of fisheries and aquaculture. The lack of data pertaining to fuel inputs to developing country fleets is particularly worrisome in the context of food security: Those countries for which the least amount of data is available, including those in Africa and southeast Asia, are often those which rely most heavily on fisheries as a source of food and employment and which in turn are more vulnerable to impacts from energy price increases (Pelletier *et al.*, 2014).

Inferring fuel use of small-scale and artisanal fisheries from the current breadth of data is difficult. The dependence of many communities in developing countries, particularly in coastal Africa, on fisheries for small pelagic species and coastal fisheries suggests that fuel inputs may be low. Furthermore, the prevalence in some areas of non-motorized vessels and the use of coast-based gears would support the idea that these fisheries are less intensive than their larger, more industrialized counterparts. However, fishing cost data from the FAO (2007) show that fisheries in developing countries spend a substantial amount on fuel when compared to those in developed countries, as a percentage of total fishing costs; while this reflects, to some degree, lower costs of labour in these countries, it also suggests the possibility of higher input of, and therefore expenditure on, fuel.

Addressing this lack of data in developing countries is paramount in identifying the potential impact of rising fuel costs on fishery-dependent communities and countries. Moreover, understanding current fuel consumption in small-scale artisanal fisheries can provide a baseline from which to evaluate and ideally inform any process of fishery industrialization. Such a transition has already been identified in India as having a substantial effect on the fuel use of fisheries there, increasing consumption tenfold between 1961 and 2010 (Vivekanandan *et al.*, 2013).

Within modern industrialized fleets, it is easier to draw conclusions from available fuel use data, even where data for a particular region are lacking. Analysis of our database shows that variation in FUI is more closely associated with species class and gear type than with region. While variations between regions certainly exist, the combination of species and gear can be considered a relatively reliable predictor. Fisheries in North America, where fewer data are available, for example, can be expected to follow similar patterns to those in Europe. Likewise, South American purse seine fisheries for small pelagic species, which are among the largest in the world, can be expected to have a FUI similar to that of other purse seine fisheries targeting large aggregations of small pelagics (generally under 100 L/t). Thus, large gaps in the database can, to some degree, be estimated with a reasonable degree of confidence. Region-specific, and even fishery-specific energy assessments, however, are always preferable to estimates based on similar fisheries, as these broader generalizations fail to incorporate local effects such as stock abundance, environmental conditions, gear and related technological choice, and management regime.

2.5.3 Improving fuel use intensity

Recent analyses of fuel inputs to European and Australian fisheries (Anderson and Guillen, 2011; Cheilari *et al.*, 2013; Parker *et al.*, 2015a) suggest that FUI of fisheries has been decreasing over the past decade. This is particularly the case in some fuel-intensive fisheries in Australia, including those targeting prawns and tuna (Parker *et al.*, 2015a). This trend of improvement has also been identified for specific fisheries in Sweden (Ziegler and Hornborg, 2014), and for some major tuna fisheries (Tyedmers and Parker, 2012). Importantly, lower rates of fuel consumption observed in many fisheries have not completely counteracted the increase in the cost of fuel, and these fisheries are facing consistent increases in their overall expenditure on fuel.

Recent trends of declining FUI are a reversal of trends observed throughout the 1990s and early 2000s (Tyedmers, 2004). This could be the result of increased awareness of fuel expenditure related to higher oil prices, improvements in technology, rebuilding of previously overfished stocks, or changes in fishing capacity and management. Evidence from Sweden suggests that improved stocks are more likely to explain improvements in fuel performance than are technological improvements (Ziegler and Hornborg, 2014). Supporting this, a decrease in stock biomass and an increase in fishing capacity led to a substantial increase in FUI of New England fisheries in the 1970s and 1980s (Mitchell and Cleveland, 1993). Recent improvement in fuel consumption of some Australian fisheries is likely linked with decreased fishing capacity: the Northern Prawn Fishery in particular has experienced a marked drop in fuel use rates since a broad government vessel buyout starting in 2005 (Parker *et al.*, 2015a; Pascoe *et al.*, 2012). Evidence of rebuilding stocks in Europe, coinciding with reductions in over-capacity (Cardinale *et al.*, 2013) may explain the apparent improvement in fuel performance of European fisheries in recent years, and hints that this improvement is likely to continue.

Technological innovation, vessel size and power, and fishing behaviour have also been suggested as potential drivers of changes (both positive and negative) in fuel consumption of fishing fleets (Mitchell and Cleveland, 1993; Schau *et al.*, 2009; Vázquez-Rowe and Tyedmers, 2013). However, evidence of the impact of technology and vessel characteristics seems to be mixed. Larger vessels, for example, have been found to be associated with higher fuel consumption in Danish fisheries (Thrane, 2004) and global tuna fisheries (Tyedmers and Parker, 2012), lower fuel consumption in the Portuguese sardine fishery (Almeida *et al.*, 2013), and mixed influence in some Baltic fisheries (Ziegler and Hornborg, 2014). While there are certainly improvement opportunities for fisheries relating to new technologies and fuel-efficient practices, stock abundance and capacity are more likely drivers. Furthermore, small improvements resulting from technological developments are likely to be overshadowed by the greater influence of species and gear. In this regard, management decision-making that intentionally or unintentionally re-allocated harvest between gear sectors can have a surprising impact on resulting fleet-wide FUI, either positively or negatively. This was demonstrated by Driscoll and Tyedmers (2010), who found that a management-related shift from mid-water trawlers to purse seines in the Atlantic herring fishery could easily result in reductions in total fuel combustion of at least two-thirds.

2.5.4 Potential applications

The FEUD, and the breadth of literature and analyses that comprise it, offers a number of application opportunities. First and foremost is the ability to compare the relative energy performance—and related carbon footprint—of fisheries and their derived products. The ability to quickly assess an individual fishery or a range of products on the basis of energy use and emissions has application benefits for industry, regulators, environmental non-governmental organizations, and consumer groups. Sea Fish Industry Authority in the United Kingdom, for example, has been developing industry tools for the past several years to readily provide energy and carbon performance information to industry (Parker, 2012b; Tyedmers *et al.*, 2007). Similarly, Seafood Watch in the United States is exploring opportunities to incorporate metrics of energy use in their consumer-oriented assessments of fisheries and aquaculture products (Parker, 2012a).

As fuel can be used as a general proxy for the relative carbon footprint of fisheries-derived products, comparisons between fisheries and other food production systems are also possible. Figure 2.2 presents a comparison of fisheries from FEUD to other forms of protein production, on the basis of carbon footprint prior to processing and transport. It is clear that FUI greatly impacts how fish products compare to other forms of protein production. Fuel-intensive crustacean fisheries are among the least fuel-efficient forms of protein production, while less intensive small pelagic fisheries rank among the most efficient. It is important to note, however, that, in developed countries, landings from these highly efficient small pelagic fisheries are more often used for production of livestock and aquaculture feed than for direct human consumption.

With fuel’s important role in the financial performance of many fisheries around the globe, the collection and analysis of FUI data is an essential component for economic analyses. Fuel analyses help inform indicators of economic health of individual fisheries and allow for the tracking of economic performance over time. Perhaps more pertinent to policy makers, analyses of fuel consumption and costs can also provide insight into the relative impacts expected to be felt by fishers in response to fuel taxes, carbon taxes, emission regulations, and energy price increases.

2.6 Conclusions

Many fisheries, particularly those targeting small pelagic species, are among the most energy- and carbon-efficient forms of protein production. However, high-value crustacean fisheries rank amongst the more energy- and carbon-intensive forms of protein production, with the exception of ruminant livestock production systems. Furthermore, small pelagic fisheries, while an important source of food in some developing countries, are often overlooked as a food option in developed countries and instead used as an intermediate product in aquaculture and livestock production, foregoing the potential energy and carbon benefits of these fisheries as a food source.

European and Australian fisheries exhibited signs of improvement in their energy consumption during the first decade of the 21st century. This reversal of previous trends suggests that fishers may be adapting – via behavioural changes or technological innovation – to rising fuel costs. It may also be an indication that fleets are fishing more efficiently as a result of management efforts to rebuild stocks and counter the challenge of over-capacity. While the trend in FUI is encouraging, particularly if viewed as a proxy for management effectiveness, fuel subsidies to

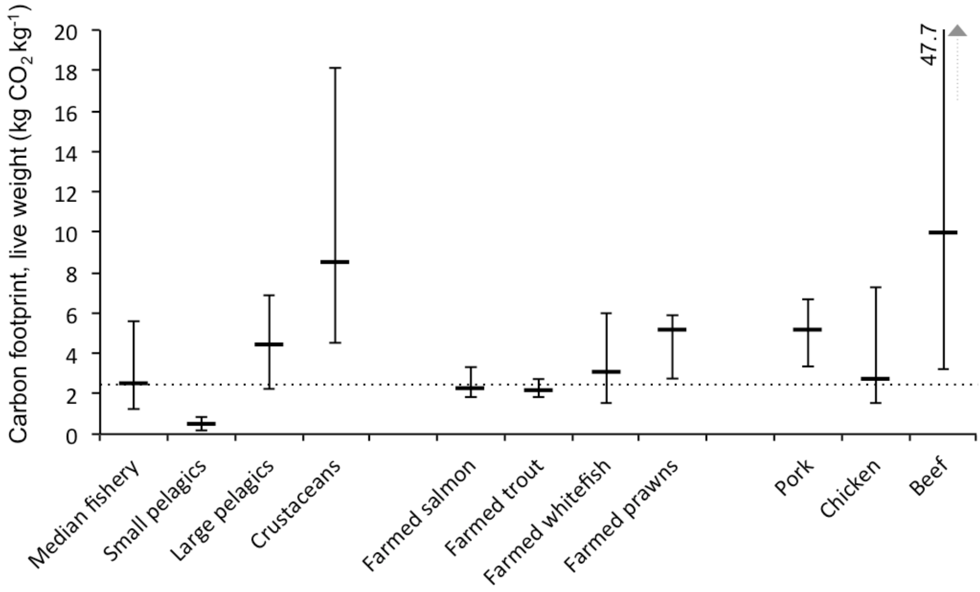

Figure 2.2. Median expected GHG emissions of different forms of fisheries, aquaculture, and livestock, showing median and range of results (reflecting 25th and 75th percentiles of observed fisheries FUI from the current study, and range of reported carbon footprints for other sources). Sources of data for aquaculture and livestock: Aubin *et al.* (2009), Ayer and Tyedmers (2009), Baruthio *et al.* (2008), Boissy *et al.* (2011), Cao *et al.* (2011), Nijdam *et al.* (2012), Papatryphon *et al.* (2004), Pelletier *et al.* (2009), Sonesson *et al.* (2010), Sun (2009).

fisheries risk delaying adaptation to rising costs and contributing to unsustainable fishing practices.

The role of fisheries as a source of income, employment and food in developing countries necessitates further research into the energy performance of their fisheries. Little research is available on the performance of small-scale fisheries, coastal fisheries and artisanal fisheries. Research will need to be undertaken to assess the economic role of fuel in developing country fisheries that are transitioning to motorized fleets, facing high relative fuel costs of fishing, and switching to more energy-intensive seafood choices as their populations become more affluent.

Fisheries are likely to face continued pressure on their profitability by rising fuel costs and carbon-related regulations in coming years. Technological innovations, behavioural changes and consideration of the energy-related effects of management decisions may be necessary to help fisheries adapt in the short term. However, the most effective way to improve the energy performance of fisheries facing these challenges will be to rebuild stocks and manage capacity effectively.

Chapter 3. Greenhouse gas emissions from world fisheries

This chapter is currently being prepared for journal submission. The research was funded in part by the Australian Seafood Cooperative Research Centre. Names and institutions of contributing authors are:

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3.1 Abstract

Human food production contributes a quarter of anthropogenic greenhouse gas (GHG) emissions globally. This proportion is unlikely to diminish and may increase over the balance of the century, as diets become increasingly carbon intensive. Marine fisheries constitute a major source of animal protein and are critically important to the livelihoods and food security of many nations, yet are typically excluded from global assessments of food production. Here we estimate the GHG emissions of the global marine fishing industry, and compare its emissions to those from agriculture and livestock production. Up to the point of landing, fisheries generated 168 million tonnes of carbon dioxide-equivalent emissions in 2011. Overall emissions were highest in Asia, while the most carbon-intensive fleets were located in countries that disproportionately targeted crustacean species. Though fisheries only account for 3% of global food production emissions, of major concern is that the industry's emissions

grew by 28% between 1990 and 2011, with no coinciding increase in production. Poor management, over-capacity, fuel subsidies, and increased activity of carbon-intensive sectors have contributed to rising emissions. To compound this, many of the products of the world's most carbon-efficient fisheries – representing some of the most climate-friendly sources of animal protein globally – are directed to industrial production of fishmeal rather than to direct human consumption. Improving carbon performance through management and fuel reduction measures would not only respond to demands for low-carbon food products, but would also increase the economic resilience of fisheries – and those countries that rely upon them – to volatile energy prices.

3.2 Introduction

Production, distribution, and consumption of food contribute unequivocally to global climate change, accounting for a quarter of anthropogenic greenhouse gas (GHG) emissions (Smith *et al.*, 2007; Steinfeld *et al.*, 2006). Agriculture and livestock sectors contribute over half of global non-carbon dioxide (CO_2) GHG emissions, including methane and nitrous oxide (Smith *et al.*, 2014). Production of animal protein, in particular, is a substantial and growing driver of global warming, responsible directly and indirectly for up to 20% of emissions (Garnett, 2009; Pelletier and Tyedmers, 2010; Smith *et al.*, 2014; Steinfeld *et al.*, 2006). As income and affluence in developing countries increase and diets approach the meat-rich consumption of the developed world, emissions associated with food production, and animal protein in particular, are likely to increase at least up until the middle of this century (Fiala, 2008; Popp, 2010; Tilman and Clark, 2014). A continuation of this trend could see an increase in diet-related emissions of over 30% by 2050 (Tilman and Clark, 2014).

Transitioning to diets with little to no red meat or completely vegetarian diets can potentially decrease per capita food-related emissions by over 50% (Carlsson-Kanyama, 1998; Nilsson and Sonesson, 2010; Tilman and Clark, 2014). Tracking and decreasing emissions from animal production protein is an important component of global initiatives to limit climate change while still meeting the food needs of a rising population.

Global fisheries, a critically important source of nutrition and income around the world, are underrepresented in discussions on GHG emissions in food production. Assessments typically either exclude fisheries entirely (Foley *et al.*, 2011) or generalize based on minimal data (FAO, 2013a; Tilman and Clark, 2014), failing to recognize the vast variation in emissions between fisheries targeting different species and operating different gears (Parker and Tyedmers, 2015). While not associated with the wide range of direct and indirect GHG emissions produced from land-based meat production (Garnett, 2009; Steinfeld *et al.*, 2006), fisheries are often energy-intensive operations and produce the majority of their emissions from burning fossil fuels. Further, there is marked variation both across and within fleets in the amount of energy it takes to catch fish (Parker and Tyedmers, 2015; Pelletier *et al.*, 2011; Tyedmers, 2004). As national and international government initiatives to curb carbon emissions continue to develop in coming years, it can be expected that the emissions profile of food production systems and diets will receive increased attention. Without consideration of fisheries, including the vast variation present within the sector, the picture of global GHG emissions from food production is incomplete and potentially misleading.

In this paper, we quantify the GHG emissions of the global fishing fleet, in terms of absolute volume of emissions and emissions intensity per tonne of round-weight landings. We provide the first global breakdown of wild-capture fishery emissions by fishing country, and compare each nation's fishery emissions against those from agriculture and livestock production. We present results from analysis of the aggregate emissions of national fishing fleets, as well as the intensity of emissions per unit of landed fish, which can vary dramatically depending on the types of fishing (species, gear) conducted in each country. While accounting for only 3% of food production emissions globally, we demonstrate that fisheries can contribute substantially to the national emissions of the countries that rely most heavily upon them. We show that the global industry has become less efficient in recent decades, estimating a 28% increase in emissions from 1990 to 2011 while landings remained relatively constant, and we discuss the possible factors leading to this increase in carbon intensity and how to reverse this trend.

3.3 Methods

Estimates of fishing effort were sourced from a global database based on estimates of total vessel engine size and number of fishing days in a year, assembled from FAO, the EU, regional tuna management bodies, and other sources (Anticamara *et al.*, 2011; Watson *et al.*, 2013). Number of fishing vessels, gross registered tonnage, and gear type were sourced from the FAO Fishing Fleet online database. The EUROPA Fishing Fleet Register online database provided detailed data about vessel characteristics for EU country members. These data sources were augmented by data from regional tuna associations and various online sources to provide in depth information about fleet sizes and characteristics, but also, importantly, information about the number of days that this fishing capacity was employed each year.

Emissions from each fishery sub-sector, specific to species, gear, and country, were calculated based on estimates of fuel use intensity (FUI), in litres of diesel required to catch one tonne of round weight landings. Observed and calculated FUI values for fishing vessels and fleets were taken from the Fisheries and Energy Use Database (FEUD) (Parker and Tyedmers, 2015). The database contains a total of over 1,600 records of fuel use, vessel characteristics, and landings at various scales of operation (*e.g.* individual vessels and national and global fleets). For this analysis, records for pre-1985 fisheries were excluded.

For each fishery, fuel use records were matched to landings based on country, gear type, and target species. Where multiple FUI records were drawn upon for a single fishery, and satisfied both species- and gear-specific criteria, estimates were weighted by year (applying 10% less weight per year of difference between fishing year and estimate year), and inverse-weighted to remove selection bias towards sources reporting multiple estimates. In cases where species-specific FUI estimates were not available, matches were based on a set of 30 target groups of species sharing similar characteristics and habitats (*e.g.* pelagic species <30cm). In cases where country-specific FUI estimates were not available, estimates reflect similar fisheries (operating the same gear and targeting the same species or group of species) in other regions. This produced a hierarchy of values, from which the most specific match (matching species or target group, gear, and country) was selected.

Estimates of non-motorized landings were made based on a) the relative possibility of individual gear types being non-motorized, and b) the reported number of non-motorized vessels in each country's fleet according to the FAO (2014). Because of limited data, artisanal rates for many countries were estimated from neighbouring countries and/or countries with similar socio-economic and fishing conditions. Artisanal landings were assumed to have nil fuel use up to the point of landing, and were so discounted from the fuel consumption of each country.

Greenhouse gas emissions were estimated using a ratio of fuel to emissions of 3.1 kg CO_2-eq per litre of diesel. An average density of 0.9 kg/L was assumed, with a carbon content of 860 g/kg, resulting in direct emissions of 2.8 kg CO_2-eq from burning fuel. Upstream emissions associated with mining, refining, and distributing diesel fuel account for an additional 0.3 kg CO_2-eq based on life cycle inventory data from the ecoinvent 3.0 database (Weidema *et al.*, 2013). Based on life cycle assessments (LCAs) of fisheries over the past decade (Avadí and Fréon, 2013; Parker, 2012b; Vázquez-Rowe *et al.*, 2012a), it was estimated that fuel-related emissions accounted for 75% of the total emissions profile up to the point of landing. Consequently, emissions were further multiplied by 1.33 to account for vessel construction and maintenance, gear manufacture, refrigerants, and other activities. In order to avoid double counting, no additional emissions were added to bait-using fisheries, as it was assumed that most bait was sourced from other fisheries for which landings and emissions data were available. In the case of artisanal fisheries, fuel inputs to fisheries with the same target group and gear type were used to estimate the relative yield efficiency of those fisheries for the purpose of allocating emissions from non-fuel inputs (vessel construction, gear manufacture, etc.); that is, the non-fuel emissions from artisanal fisheries were assumed to be equal to the non-fuel emissions of their motorized counterparts.

National fishery GHG emissions were compared against agricultural emissions using data reported in the FAOSTAT Emissions Database (FAO, 2013a). All emissions associated with direct food production from agricultural and livestock production were included. Emissions associated with the burning of savanna and forestland were excluded as they was not considered to be directly related to food production, and greatly expanded agricultural emissions in some countries where burning is required for multiple reasons such as fire prevention and forest regeneration.

Fish landings were allocated to the non-food sector on the basis of target group, with 75% of non-food landings from fisheries targeting pelagic species under 60cm in length and 25% from other fisheries (FAO, 2013c). Reduction fisheries were assumed to be sourced entirely from fisheries targeting pelagic species under 60cm in length. Country of origin for reduction fisheries was based on global fish meal production data from the United States Department of Agriculture (USDA, 2014), and production in Europe was further disaggregated based on the relative rate of small pelagic harvests in European countries.

3.4 Results and Discussion

3.4.1 Emissions of national and global fishing fleets

By combining species- and gear-specific fuel use data with reported catches from national fleets, we estimated that world's fishing fleets in 2011 emitted 168 million tonnes of carbon-dioxide equivalent (CO_2-eq) GHGs to the atmosphere, or 2.1 kg

CO_2-eq per kg landed fish and invertebrates. Based on emission profiles from life cycle assessments of fishery products (Avadí and Fréon, 2013; Parker, 2012b), three quarters of atmospheric emissions were modeled to result directly from combustion of fossil fuels onboard fishing vessels. The remaining emissions are attributed to upstream extraction, refining, and transport of this fuel, as well as other activities such as construction and maintenance of the vessel and use of refrigerants.

The national fishing fleets with the largest overall GHG emissions were based in China, Indonesia, India, Japan, and the United States (Figure 1). These five countries accounted for 38% of landings and 48% of total emissions in 2011, producing 81 million tonnes CO_2-eq. The substantial contribution to fishery emissions from Asia reflects the extent of fishing, and the scale of fleets based in the region. Chinese-based fishing fleets alone emitted 47 million tonnes CO_2-eq, approximately one quarter of total global emissions from fisheries and surpassing the combined impact of all fisheries in Europe and the Americas. Countries that disproportionately targeted crustaceans had more carbon-intensive fleets, including Saudi Arabia and Australia. The extreme of low emission production occurred off the west coast of South America, which accounted for 14% of global fisheries production in 2011 but only produced 3% of fishery-sourced emissions as a result of the relatively high percentage of landings from the low-intensity Peruvian anchovy (*Engraulis ringens*) fishery. European and African countries that similarly targeted small pelagic forage fish also produced fewer emissions.

The drivers behind national comparisons are evident when looking at individual countries with diverse fleets. Fisheries in the United States, for example, together had the third highest emissions in 2011, but were amongst the most efficient in terms of average emissions intensity (Figure 3.1). The largest fisheries in the U.S. include two very low-input small pelagic fisheries targeting Gulf menhaden (*Brevoortia patronus*) and Atlantic menhaden (*Brevoortia tyrannus*), as well as the Alaskan pollock (*Gadus chalcogrammus*) trawl fishery which consumes relatively little fuel compared to similar whitefish fisheries (Fulton, 2010; Tyedmers, 2004). Fisheries for these three species made up over 40% of the total 5.2 million tonnes harvested by U.S. fleets in 2011. Australian fisheries harvest substantially lower volumes than those of many other countries but disproportionately target high-value species, including rock lobsters and prawns. These fisheries require fuel inputs several orders of magnitude greater than those to many small pelagic fisheries. As a result, while contributing little to overall global emissions, Australian fleets were amongst the most carbon-intensive in 2011, with an average emissions intensity several times that of the U.S. fleet.

3.4.2 Emissions by fishing sector

Disaggregating national fleets by species class, it is evident that the contribution to overall fishing emissions varies dramatically between sectors (Table 3.1). Fisheries for pelagic species under 30cm in length, which account for a quarter of reported landings, make up only 2% of global emissions. Crustacean fisheries, meanwhile, account for only 5% of landings but over 20% of emissions. Fisheries for lobster and shrimp harvest relatively low volumes per trip compared to those targeting finfish and, particularly in the case of trawl fisheries targeting crustaceans, consume substantial quantities of fuel in the process.

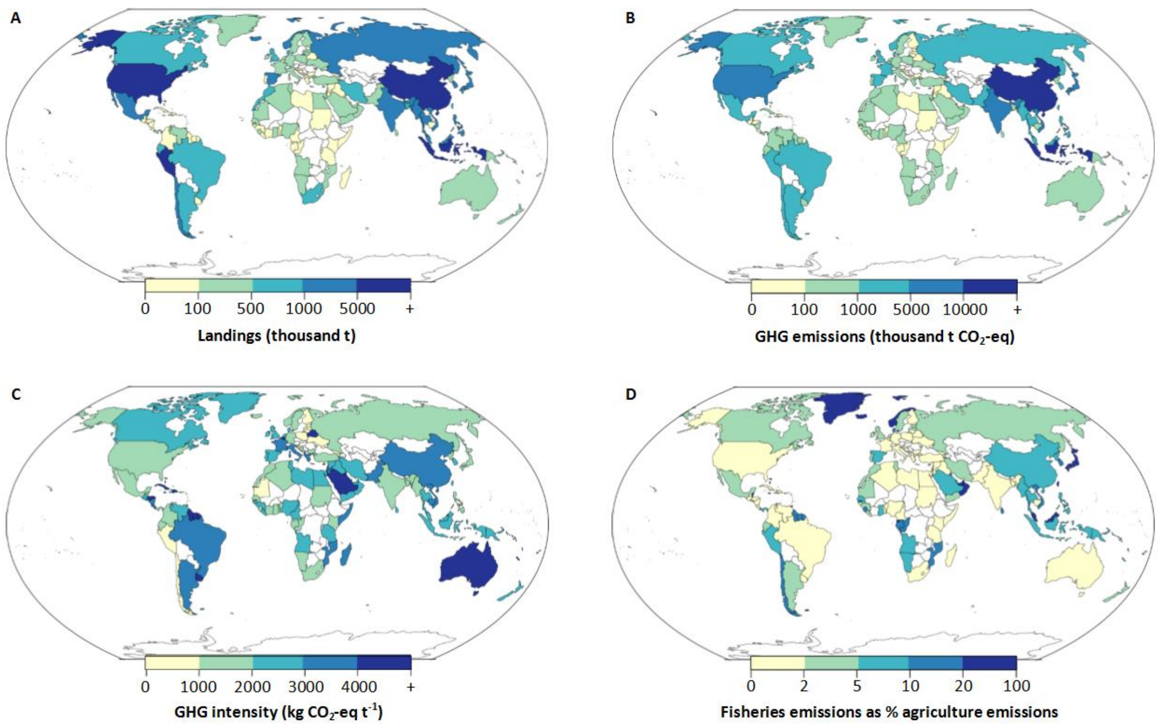

Figure 3.1. (A) Landings by national fishing fleets in 2011, millions of tonnes; (B) aggregate GHG emissions by national fishing fleets, up to the point of landing, thousands of tonnes CO_2-eq; (C) emissions intensity of fishery landings, kg CO_2-eq per tonne; (D) GHG emissions from fisheries as a percentage of emissions from agricultural production. See Appendix B for results by country.

Related to the high efficiency associated with small pelagic species is the relatively minor contribution to emissions from non-food sectors, particularly the global fishmeal and oil industry. Upwards of a third of global marine fisheries landings are used for non-food purposes (Deutsch *et al.*, 2007; FAO, 2013c; Watson *et al.*, *in press*).

Most of this is destined for reduction into meal and oil to be used as ingredients to aquaculture and livestock feeds, sourced largely from small pelagic fisheries in Chile, Peru, Thailand, Europe, China and the United States (Tacon and Metian, 2008; USDA, 2014). These fisheries were estimated to produce 4% of the global industry's emissions in 2011, or approximately 0.3 kg CO_2-eq per landed kilogram of fish. While vessel efficiency in reduction fisheries can vary markedly between fleets(Cashion *et al.*, in review), they are consistently less carbon-intensive than other sectors. At this rate, if fish landed by reduction fisheries were instead directed to human consumption, their products could potentially be associated with lower emissions than every other major source of animal protein. This, of course, would require both a market for such products and a means to limit emissions post-landing, and would further necessitate the substitution of non-fishery feed inputs to aquaculture systems as farm-based fish production continues to grow.

The non-motorized fishing sector was estimated to account for six million tonnes of landed fish and invertebrates in 2011. The vast majority of these landings were in Africa and Asia, based on estimated percentages of non-motorized fishing vessels by country in these regions (FAO, 2014). Non-motorized vessels are still associated with some non-fuel emissions, but contribute less than 2% to overall atmospheric

Table 3.1. Greenhouse gas emissions, per tonne and industry-wide, of different sectors of world fisheries in 2011.

Industry sector	**Landings (million t)**	**Emissions intensity (kg CO_2-eq/kg)**	**Total emissions (million t CO_2-eq)**
Global fisheries	81	2.1	168
By vessel type			
Motorized	74	2.2	164
Non-motorized	6	0.7	4
By product type			
Human consumption	57	2.5	143
Non-food products	24	1.0	25
Meal and oil	18	0.3	6
By species group			
Pelagic <30cm	17	0.2	3
Pelagic >30cm	21	1.8	38
Demersal molluscs	3	2.2	6
Demersal	31	2.3	70
Cephalopods	4	2.6	10
Crustaceans	5	7.5	41
By region			
Latin America	16	1.0	15
North America	6	1.6	9
Europe	12	1.6	19
Africa	5	1.7	8
Asia (exc. China)	28	2.4	66
Oceania	1	2.7	3
China	14	3.5	47

emissions from the industry. A potential source of concern for fisheries management in developing countries is the expected increase in reliance on fossil fuels as fleets shift from traditional methods to energy-intensive industrialized operations (Boopendranath and Hameed, 2013), particularly as fuel use in these regions already accounts for a relatively larger portion of fishing costs (FAO, 2007) and increased costs could potentially threaten the ability of subsistence and small-scale operators to fish.

3.4.3 Trends in emissions from marine fisheries 1990-2011

Total landings from the world's fishing fleets, as well as the relative mix of pelagic, demersal, and invertebrate species, remained relatively unchanged over the period from 1990 to 2011 (Figure 3.2). Fluctuations throughout the period were driven primarily by varying harvests of small pelagic species, particularly the Peruvian anchovy fishery off the coast of Peru and Chile (see for example the drop in landings corresponding with the El Niño event in 1998).

In contrast, emissions from world fisheries grew 28% over the past two decades, contributing 37 million tonnes CO_2-eq more GHGs to the atmosphere in 2011 than in 1990 (Figure 2). Average emissions intensity of the industry was over 20% higher in 2011 than in 1990, with noticeably higher emissions in years with relatively low landings of small pelagics, including 1998 and 2010. Some of the increase in emissions over this time period is attributable to species mix, in particular, landings from high-input crustacean fisheries increased by 60% over the same period. The increasing trend in emissions intensity throughout the 1990s and early 2000s, has been reported in fleet- and region-specific research in Europe (Cheilari *et al.*, 2013;

Guillen *et al.*, *in press*), the North Atlantic (Tyedmers, 2001), and Australia (Parker *et al.*, 2015a).

3.4.4 Comparison to agriculture

Global emissions from agriculture and livestock production, excluding those associated with burning savanna and cropland, amounted to 5 billion tonnes CO_2-eq in 2011 (FAO, 2013a). Emissions from fisheries, at 168 million tonnes, account for approximately 3% of the combined impact from fishery and agricultural production. In approximately half of the world's countries, including almost all industrialized nations, fisheries account for less than 5% of the emissions associated with food production (Figure 3.2). However, in some coastal and island countries, including Kiribati, the Marshall Islands, and the Maldives, where most domestically-produced protein comes from the ocean and agriculture is limited, fisheries account for almost all food production emissions. Among industrialized countries, fisheries in Iceland (79% relative to agriculture), Greenland (70%), Norway (37%), Japan (20%), and Denmark (11%) contribute substantially to national food-production related emissions, reflecting the role that fisheries play in the economies, diets, and cultures of those countries.

3.4.5 Reducing emissions from fisheries

There are both environmental and economic incentives to reduce energy use and GHG emissions in the global fishing industry. The direct relationship between fuel consumption and emissions in fisheries (Parker and Tyedmers, 2015), and the relative

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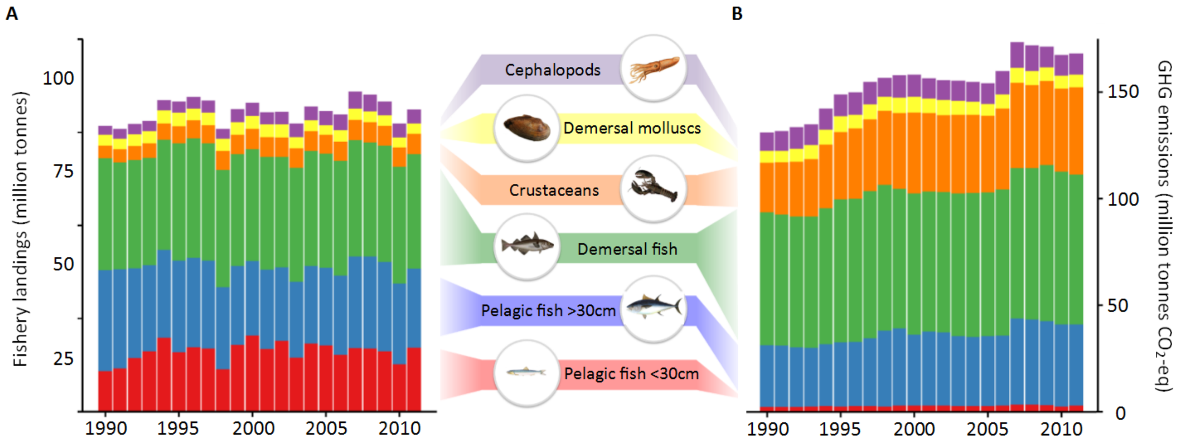

Figure 3.2. (A) Global landings, in millions of tonnes, of fish and shellfish from world fishing fleets, divided by species groups; (B) GHG emissions, in millions of tonnes of CO_2-eq, from global fisheries, divided by species groups.

as of yet – lack of large-scale adoption of alternative energy sources in commercial fishing vessels, such as sail-assisted propulsion or hydrogen-powered engines (Arnason and Sigfusson, 2000; Sterling and Goldsworthy, 2007), means that the most effective means of reducing emissions is through reducing fuel inputs to fishing vessels. Fuel is the second largest cost to fishing operations worldwide, particularly in regions where wages are low (Lam *et al.*, 2011). Improving rates of fuel use—directly through technological or behavioural changes or indirectly via management—would therefore be an effective means of reducing costs and improving resilience of fleets to volatile energy prices.

The effect on fuel consumption of numerous behavioural, technological, and managerial changes have been assessed, with mixed results. Identifying those factors that influence fuel use most, and can therefore yield potential for improvement, is difficult: both the direction and magnitude of relationships between fuel use and variables such as vessel size and engine horsepower vary from fishery to fishery (Guillen *et al.*, *in press*; Ziegler and Hornborg, 2014). Smaller vessels have been identified as more efficient in some Danish fisheries for example (Thrane, 2004), but less efficient in European beam trawlers and dredgers (Guillen *et al.*, *in press*). Behavioural changes, such as reducing vessel speed while steaming and being more selective of fishing times and locations, are often suggested as short-term adaptations to increased fuel prices that are easily implemented by fishermen (Abernethy *et al.*, 2010). Indeed, the skill and experience of skippers can explain variation in efficiency within fleets (Ruttan and Tyedmers, 2007; Vázquez-Rowe and Tyedmers, 2013).

Long term improvement of the industry's efficiency, however, must come from improved management of stocks and reduction of fishing capacity (Ziegler and Hornborg, 2014). The Northern Prawn Fishery in Australia, for example, witnessed a dramatic improvement in fuel performance after a government-sponsored buyback of vessels (Parker *et al.*, 2015a; Pascoe *et al.*, 2012). Reductions in fuel inputs to European fisheries have been observed in recent years, and have been attributed at least partially to increased stock biomass (Guillen *et al.*, *in press*; OECD, 2012; Ziegler and Hornborg, 2014). Substantial decreases in fuel use after 2005 were observed in Taiwanese fleets after a reduction in the number of fishing vessels (Hua and Wu, 2011). Decreased catch rates in offshore Korean fisheries, however, resulted in rising rates of fuel use between 2011 and 2013 despite vessel number reductions (Park *et al.*, 2015). The observed influence of management factors on fuel use is several times that of technological changes alone, with potential for improving fuel consumption via management by 20-80% (OECD, 2012). In addition, long-term management-induced improvements are less likely to be reversed in years of low oil prices, as can be expected with cost-related behavioural adaptations.

The overall global trend in the period assessed here saw an increase in emissions intensity outweighing any changes in technology or behaviour over the same time frame. Slight improvements in fuel consumption and emissions have been observed in European and Australian fisheries, related to management decisions to target high stock biomass by reductions in fishing catch and capacity (Guillen *et al.*, *in press*; Parker *et al.*, 2015a). However, much more dramatic improvement may be needed if fisheries are to respond effectively to consumer demands for green products as well as economic pressure from rising costs.

A particularly contentious barrier to reducing the fishing industry's fuel use is the wide scale presence of subsidies. Estimates suggest that annual fuel subsidies and tax concessions amount to between 4.2 and 8.5 billion US dollars globally (Harper *et al.*, 2012; Sumaila *et al.*, 2010). These serve to mask the true cost of operations, encouraging fleets to maintain inefficient behaviours and technologies rather than develop more efficient operations and retire inefficient vessels and equipment. Subsidies in well-managed fisheries may not encourage overfishing, but will delay improvements in energy use and GHG emissions—issues that may not have been of concern when the subsidies were originally implemented. In fisheries that are not effectively managed to maintain healthy stocks, fuel subsidies can allow operations to persist despite reduced catch rates; in those cases, removal of fuel subsides, while resulting in high short-term costs, could lead to improved efficiency and reduced costs in the long-term (Arnason, 2007). As an added benefit, the reduction in fishing effort that would be experienced if fishing costs reflected the true cost of energy inputs could allow overfished stocks to rebuild and provide for higher yields, lower fishing costs, and lower emissions in future years.

Chapter 4. Environmental and economic dimensions of fuel use in Australian fisheries

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4.1 Abstract

Fisheries globally are facing multiple sustainability challenges, including low fish stocks, over-capacity, unintended bycatch and habitat alteration. Recently, fuel consumption has joined this list of challenges, with increasing consumer demand for low-carbon food production and implementation of carbon pricing mechanisms. The environmental impetus for improving fishery fuel performance is coupled with economic benefits of decreasing fuel expenditures as oil prices rise. Management options to improve the fuel performance of fisheries could satisfy multiple objectives, by providing low-carbon fish products, improving economic viability of the industry, and alleviating pressure on overfished stocks. We explored the association of fuel consumption and fuel costs in a wide range of Australian fisheries, tracking trends in consumption and expenditure over two decades, to determine if there is an economic

impetus for improving the fuel efficiency – and therefore carbon footprint – of the industry. In the years studied, Australian fisheries, particularly energy-intensive crustacean fisheries, consumed large quantities of fuel per kilogram of seafood product relative to global fisheries. Many fisheries improved their fuel consumption, particularly in response to increases in biomass and decreases in over-capacity. Those fisheries which improved their fuel consumption also saw a decrease in their relative fuel expenditure, partially counteracted by rising oil prices. Reduction in fuel use in some Australian fisheries has been substantial and this has resulted not from technological or operational changes but indirectly through fisheries management. These changes have mainly resulted from fisheries management decisions targeting ecological and economic objectives, so more explicit consideration of fuel use may help in extending these improvements.

4.2 Introduction

4.2.1 Fuel use and carbon emissions in fisheries

Fossil fuel consumption is the primary source of energy for modern marine fishing fleets and plays a central role in both the environmental and economic performance of fisheries. Interest in measuring, comparing and improving the energy performance of food production systems, including fisheries, first arose after the oil price shocks of the 1970s (Rawitscher, 1978; Tyedmers, 2004). The issue is of increasing pertinence in recent years as a result of rapidly increasing oil prices and concern over greenhouse gas (GHG) emissions and climate change, and implications for fishing communities (Abernethy *et al.*, 2010; Pelletier *et al.*, 2014).

In the decade from 2002 to 2011, the price of Brent crude oil rose more than 300%, increasing by an average of US$0.70 per month (EIA, 2012). After peaking in 2008, global oil prices dropped during the Global Financial Crisis, but have since increased to be consistently above US$100 per barrel. This increase in oil prices and the resulting burden placed upon diesel-consuming fisheries has easily outpaced any increase in seafood prices resulting in overall decrease in profitability (Tveteras *et al.*, 2012). The different trajectories of fuel and seafood prices has sparked concerns over the impact of such energy costs on seafood consumers and fishing communities (Abernethy *et al.*, 2010).

Tracking and improving energy performance is critical in ensuring the long-term sustainability of food production, both economically and environmentally. Changes to fishery-sourced food supply and seafood prices can have drastic socio-economic impacts, particularly in poorer countries that rely heavily on fisheries as a source of food and income (Pelletier *et al.*, 2014). These potential impacts will likely become more apparent as oil prices rise and as emissions-based regulations are put in place.

Wild harvest fisheries are unique in that the industrial energy inputs and GHG emissions of their operations, ranging from propulsion and fishing to powering cooling systems and other ancillary activities, are typically from direct fossil fuel consumption (Tyedmers, 2004). In contrast, the energy inputs and GHG emissions of land-based food production systems are largely via inputs to production of fertilizers and pesticides, soil nutrient loss and livestock emissions. Likewise, energy inputs and emissions in aquaculture systems are often dominated by upstream production of fish feeds (Pelletier *et al.*, 2011; Pimentel and Pimentel, 2003; Troell *et al.*, 2004).

Tyedmers and colleagues (2005) estimated that, in the year 2000, the global fishing fleet consumed 42.4 million tonnes of fuel and released over 130 million tonnes of carbon dioxide (CO_2). Emissions from the burning of fuel by fishing vessels typically outweigh the combined emissions associated with processing, packaging and transporting seafood products (Parker, 2012b; Sonesson *et al.*, 2010). Exceptions to this include instances where fishery products are transported via airfreight, for example, with live lobster exports (Boyd, 2008; Farmery *et al.*, 2014; van Putten *et al.*, *in press*). In addition to carbon emissions, contributions of fisheries to a wide range of airborne emissions can, in large part, be directly attributed to fuel, including sulfur dioxide (SO_2), photochemical smog particulates, and ozone-depleting substances (CFCs) (Pelletier *et al.*, 2007; Avadí and Fréon, 2013; Parker and Tyedmers, 2013).

In many fishing operations throughout the world, fuel is the second highest cost after wages to crew (Lam *et al.*, 2011). Fuel accounts for a rising portion of fisheries operating costs (Parker and Tyedmers, 2015), and is a leading source of concern for the economic viability of fishing operations and fishery-dependent communities (Abernathy *et al.*, 2010). This varies by region, with the role of fuel generally being greater in developing countries (FAO, 2007). Abernethy and colleagues (2010) surveyed UK fishermen on their observations and opinions related to the cost of fuel, and found 100% of respondents expected a “significant reduction in fishing fleet as a result of increasing fuel prices”, while 94% expressed uncertainty about the future of the industry as a result. Many of the world’s fisheries are already facing economic pressure from fleet over-capacity, declining fish stocks and highly variable ex-vessel prices; rising fuel prices will serve to exacerbate these challenges.

Analyses over the past decade have measured the fuel use intensity (FUI) of fishing fleets, expressed in litres of fuel burned per tonne of round weight landings (L/t). The FUI of many commercial fishing fleets increased throughout the 1980s and 1990s (Tyedmers, 2001). Fuel prices during those years were low enough to allow for production to occur that would not have been viable with higher prices (*e.g.* use of intensive gear types), and modest increases in costs could more easily be compensated for by technological and operational changes. This trend may have reversed since the beginning of the 21st century; European fleets have decreased their FUI since 2002 (Cheilari *et al.*, 2013). In addition to fishery-specific assessments, broad analyses of fisheries fuel consumption exist for North Atlantic fisheries (Tyedmers, 2001), Norway (Schau *et al.*, 2009), Denmark (Thrane, 2004), the European Union (Cheilari *et al.*, 2013), Japan (Watanabe and Okubo, 1989), Taiwan (Hua and Wu, 2011) and global fisheries targeting tunas (Parker *et al.*, 2015b). These analyses identified a number of consistent patterns in fuel consumption. On a macro level, FUI varied by species (related to biological measures such as biomass levels and schooling behaviour), fishing gear and location (Parker and Tyedmers, 2015). This variation is on a scale of several orders of magnitude, with some small pelagic species requiring less than 50 L/t while crustaceans such as lobsters may require several thousand L/t (Schau *et al.*, 2009; Tyedmers, 2001; Ziegler and Valentinsson, 2008). Similarly, fisheries targeting related species but using different gears also varied markedly in their fuel consumption; tuna fisheries fishing with purse seine require far less fuel than those fishing with longline and pole-and-line gears (Parker *et al.*, 2015b). On a micro level, FUI was found to be influenced by size of vessel, skipper behaviour, management rules and fishing technique, such as the use of fish aggregating devices or the choice of how far to travel to fishing grounds and whether to fish on days of poor weather (Farmery *et al.*, 2014; Parker *et al.*, 2015b; Thrane, 2004; Vázquez-Rowe and Tyedmers, 2013).

4.2.2 Australian fisheries

Australia has the third largest fishing zone in the world, owing to its geographic size, island status and territorial claims over Antarctic waters. Despite this, the relatively low productivity of its surrounding waters results in a contribution of only 0.2% to global fisheries landings. The high value of some of the main species targeted makes Australian fisheries some of the most valuable, accounting for a disproportionately high 2% of global landing value (Ridge Partners, 2010). The low-volume, high-price fisheries that drive the value of Australia's fishing industry include those targeting rock lobsters (*e.g. Jasus edwardsii*, *Panulirus cygnus*), prawns (*e.g. Penaeus esculentus*, *Melicertus plebejus*), tunas (*e.g. Thunnus maccoyii*, *Thunnus albacares*), crabs (*e.g. Portunus pelagicus*) and abalone (*e.g. Haliotis laevigata*, *Haliotis rubra*) (Figure 4.1).

Total volume of Australian wild fisheries production in 2010-11 was 163 000 tonnes, while the gross value of production (GVP) was AUD$1.3 billion (Skirtun *et al.*, 2012). Value of production has decreased steadily since 2001 as the result of declining ex-vessel prices in many of the most valuable fisheries. Federally-managed fisheries, generally located beyond the three nautical mile coastal zone, make up 29% of landings and 24% of fisheries value, while the majority of catch is taken by state-managed fisheries (Figure 4.2). Within three nautical miles of the coast, each state manages the fisheries within its jurisdiction, including those where a stock is shared with other states (*e.g.* rock lobster fisheries in South Australia and Tasmania).

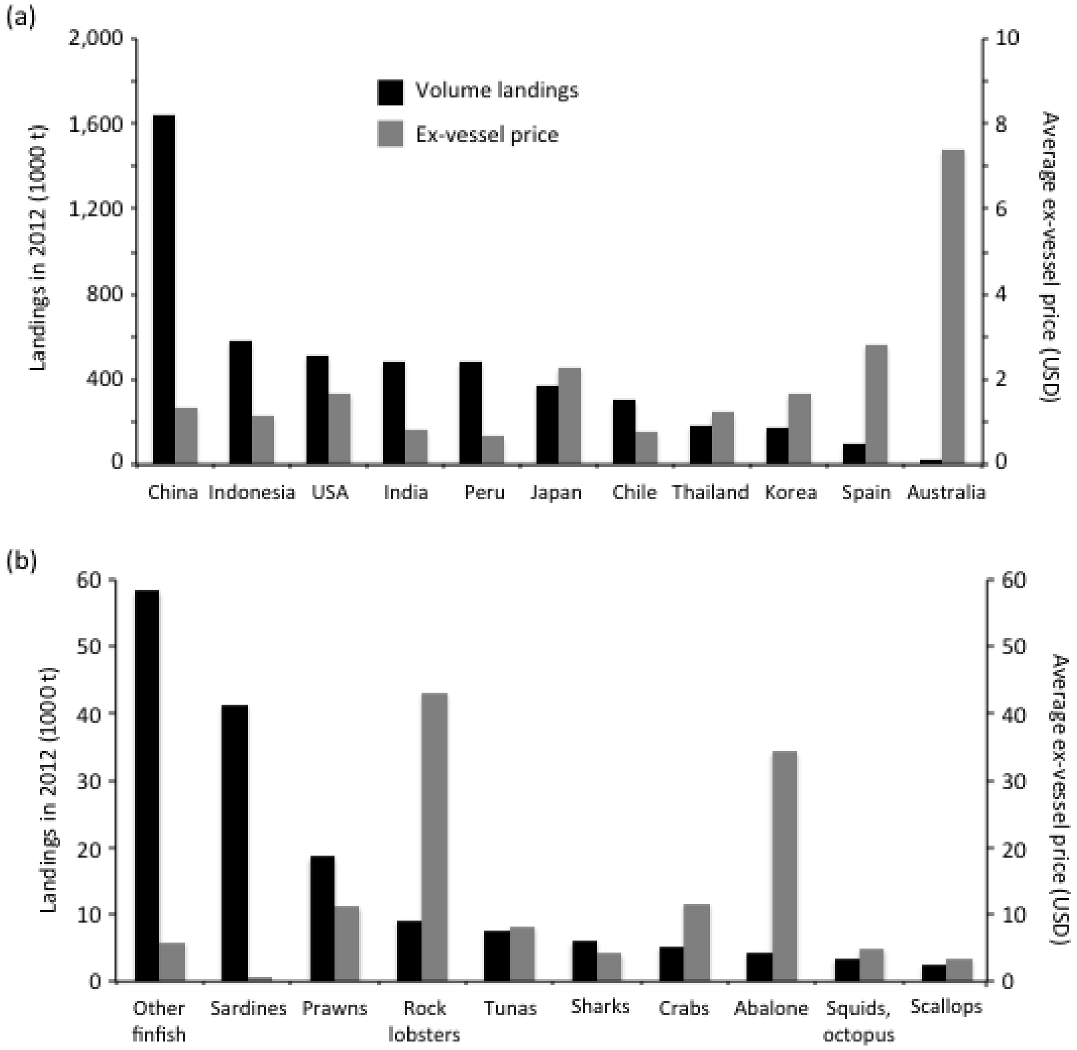

Figure 4.1. (a) Landings in 2012 and average ex-vessel price in 2005, for Australia and the top ten fishery production countries by gross value; landings data from FAO's FishStatJ, ex-vessel price for all countries except Australia from Swartz et al 2013. (b) Landings and ex-vessel prices for different species groups in Australia in 2012; data from ABARES Australian Fisheries Statistics.

Western Australia (22%) and South Australia (15%) contribute most to national fisheries GVP (Skirtun *et al.*, 2012). Australian fisheries are heavily export-oriented: 20% of production volume and 50% of production value is typically exported, primarily to East Asian markets of Japan and China; increased demand for live exports to Asia has shifted production and marketing effort to these high-value fisheries since the late 1990s. Fisheries export value, however, has also declined steadily over the past decade as prices have dropped (Ridge Partners, 2010).

The effect of fuel costs on fishing is of special interest for Australian fisheries and Oceania more widely because this region of the world has the highest costs of fishing, with fuel representing an estimated 20% of total costs on average (Lam *et al.*, 2011). In addition, the operating environment for fisheries is changing with concerns regarding the potential effects of carbon pricing policies, if they are enacted by the federal government. Fisheries and transport were exempt from the recent Australian carbon tax. The fishing industry remains concerned over the increased role fuel plays in the economic performance of fisheries, the effect of potential carbon management options, and the limited capacity of fisheries to respond to fuel costs through efficiency measures and technological improvements (Madon, 2011; NSW Fishing Fleet, 2009).

Understanding the fuel consumption and carbon footprint of fisheries is necessary for assessing the current and future environmental and economic performance of the industry. Energy analyses contribute to economic assessments of fishing sectors, help in understanding the relative role fisheries play in food production sustainability, and can indicate potential vulnerabilities to fuel price changes and related management

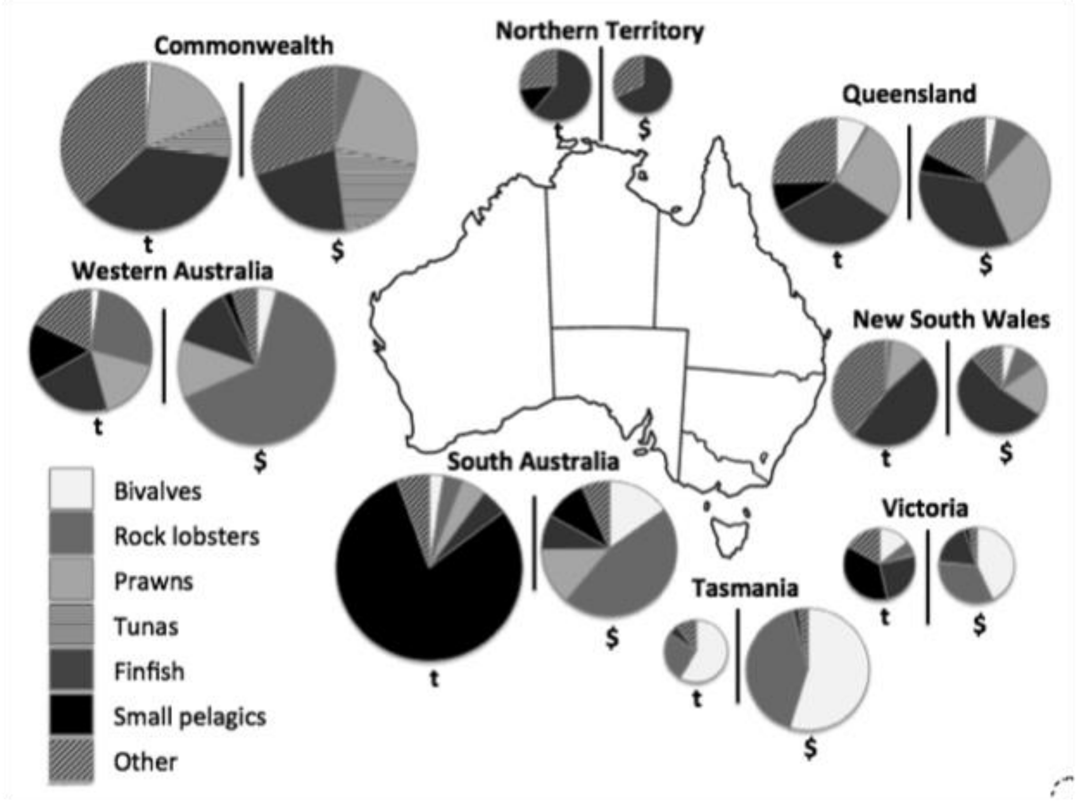

Figure 4.2. Relative landings (t) and value ($) of Australian fisheries, showing breakdown by area for each state, as well as Commonwealth (federally managed) sectors. Note that Commonwealth fisheries are located around the country, including tropical rock lobster fisheries in the northeast, prawn fisheries on the northern coast, tuna fisheries primarily in the southeast and east, and finfish fisheries in the southeast.

options. Here we report the relative FUI and fuel costs of a range of Australian fisheries, examine how fuel consumption by Australian fishing fleets has changed over time, and discuss the energy demands and carbon footprint of Australian fisheries relative to other fisheries around the world and other forms of protein production.

4.3 Methods

Cost and revenue data for a range of Australian fisheries were sourced from survey-based economic assessments by (a) the Australian Bureau of Agriculture and Resource Economics and Science (ABARES) for Commonwealth managed fisheries; (b) EconSearch Pty Ltd. for South Australian and Tasmanian fisheries, and (c) Dominion Consulting Pty Ltd. for New South Wales fisheries. Data were gathered for a total of 20 fisheries (Table 4.1). Assessed fisheries accounted for 53% of Australian fisheries landings by volume in 2010/11 and 46% of gross landed value.

The structure of the Northern Prawn Fishery (NPF) on Australia's northern coast allowed for further disaggregation to fishing seasons targeting primarily banana prawns and seasons targeting primarily tiger prawns. This disaggregation was based on season-specific effort and catch rates (Barwick, 2013).

While data for the Tasmanian rock lobster fishery were only available for 2010/11, a multiple regression of fuel consumption relative to vessel horsepower and effort allowed for an estimate of previous years' fuel use based on annual vessel and effort data collected through compulsory logbooks of the fleet.

Fuel consumption was assessed by translating fuel costs and fishing revenue to volume of fuel and round weight of landings. Average vessel landings for each fishery were estimated by dividing vessel revenue from economic assessments by average ex-vessel price per kg of landed product as reported by EconSearch and ABARES (Skirtun *et al.*, 2012). Volume of fuel was estimated by dividing vessel fuel expenditures from economic assessments by average annual offroad diesel prices (ABARES, 2012). FUI estimates used to compare fisheries included only the three most recent years for which data were available (see Table 4.1 for fishery-specific years). Fuel-related GHG emissions were calculated using 3.1 kg CO_2 per litre (Parker *et al.*, 2015b), this includes direct emissions from burning fuel as well as emissions from upstream mining, processing and transport of fuel.

The economic role of fuel use in Australian fisheries was estimated by comparing fuel costs to fishing revenue, assuming that fuel is more economically significant to fisheries which devote a larger portion of their revenues to purchasing fuel. Further, fuel costs were also compared to a subset of other fishing expenditures, including labour, vessel repairs and maintenance, and bait.

A subset of 14 fisheries had sufficient annual data to allow for more detailed comparison of FUI. For these fisheries, FUIs throughout the entire period were compared using a one-way analysis of variance (ANOVA) test. A posthoc Tukey test was used to assess whether there were significant differences in FUI between fisheries. Multiple regression analysis was used to assess the relative influence of FUI and diesel prices on the economic role of fuel use (as % of revenue).

Table 4.1. Summary of Australian fisheries included in the analysis and range of years for which data were available. Years refer to the financial year-end.

Fishery	Primary Species	Gears	Years
* Australian sardine (SA)	Australian sardine (*Sardinops sagax*)	Purse seine	2002-2011
* Southeast finfish (CW)	Blue grenadier (*Macruronus novazelandiae*), Tiger flathead (*Platycephalus richardsoni*)	Midwater trawl, seine	1993-2011
* Northern prawn fishery (CW)	Banana prawn (*Fenneropenaeus spp.*), Tiger prawn (*Penaeus esculentus*, *Penaeus monodon*)	Bottom trawl	1993-2010
* Eastern tuna (CW)	Yellowfin (*Thunnus albacares*), swordfish (*Xiphias gladius*)	Hooks and lines	1993-2011
Southern Shark (CW)	Gummy shark (*Mustelus antarcticus*)	Hooks and lines	1993-2001
Estuary General (NSW)	Mullet (*Mugil cephalus*), bream (*Acanthopagrus australis*)	Mixed	2002
Ocean Trawl (NSW)	Mixed prawns and finfish	Trawl	2002
Abalone (TAS)	Blacklip abalone (*Haliotis rubra*), greenlip abalone (*Haliotis laevigata*)	Dive	2012
* Spencer Gulf West Coast Prawn (SA)	King prawn (*Melicertus spp.*)	Bottom trawl	1998-2009
Ocean Trap and Line (NSW)	Snapper (*Pagrus auratus*), leatherjacket (*Oligoplites saurus*)	Mixed	2002
* Southern rock lobster (TAS)	Southern rock lobster (*Jasus edwardsii*)	Pots	2003-2011
* Southern rock lobster, southern zone (SA)	Southern rock lobster (*Jasus edwardsii*)	Pots	1998-2011
* Abalone (SA)	Greenlip abalone (*Haliotis laevigata*), blacklip abalone (*Haliotis rubra*)	Dive	1998-2011
* Blue Crab (SA)	Blue swimmer crab (*Portunus pelagicus*)	Pots	1998-2011
* Torres Strait Prawn (CW)	Tiger prawn (*Penaeus monodon*), endeavour prawn (*Metapenaeus endeavouri*)	Bottom trawl	1993-2008
Southern/ western Tuna (CW)	Mixed tunas and billfishes	Hooks and lines	2002
* Southern rock lobster, northern zone (SA)	Southern rock lobster (*Jasus edwardsii*)	Pots	1998-2011
* Gulf of St Vincent Prawn (SA)	King prawn (*Melicertus spp.*)	Bottom trawl	1998-2009
Abalone (NSW)	Blacklip abalone (*Haliotis rubra*)	Dive	2002
Small Pelagic (TAS)	Jack mackerel (*Trachurus declivis*), redbait (*Emmelichthys nitidus*)	Midwater trawl	2004-2006

* denotes fisheries for which long-term data were available allowing for more detailed analyses
CW = Commonwealth, **SA** = South Australia, **TAS** = Tasmania, **NSW** = New South Wales.

Trends were assessed for the same subset of fisheries. Because of varying trends in fuel prices, the study period was divided into three equal periods, and trends were assessed within each period: 1993–1999, 1999–2005, and 2005–2011 . These periods generally line up with trends of increasing fuel prices: low and stable during the first period, rising steadily during the second period, and rising more rapidly during the third period (ABARES, 2012). For each fishery, the average annual change in FUI and fuel costs relative to revenue were calculated, and regression analyses were used to determine if trends were statistically significant.

4.4 Results

Rates of fuel consumption in Australian fisheries ranged from below 100 L/t to over 10,000 L/t (Table 4.2). The most fuel-efficient fisheries included those targeting small pelagic species with seines and trawls in South Australia and Tasmania, respectively. The most fuel-intensive fisheries were those targeting Tiger prawns in the NPF and the Torres Strait, and those targeting Southern rock lobster in South Australia. The Tiger prawn season of the NPF in particular had average consumption of over 10,000 L/t in three separate years: 2004/05, 2005/06 and 2007/08.

There was a clear pattern of fisheries targeting crustaceans consuming more fuel per tonne than those targeting other species (Figure 4.3). The eight most fuel intensive fisheries assessed here targeted lobster and prawn species. Related to this, the pattern of FUI between fisheries reflected in part the relative value of fishery products. Hence, fisheries for tuna and crustaceans were more fuel intensive than those for finfish, which in turn were more fuel intensive than those for small pelagics. The

Table 4.2. Fuel use intensity, fuel-related GHG emissions, and fuel costs relative to revenue and fishing costs in Australian fisheries. Values calculated as the mean of the three most recent years for which data were available. See Appendix C for detailed annual FUI and fuel cost data by fishery.

Fishery	FUI (L/t)	CO_2 emissions (kg CO_2/kg)	Fuel costs (% revenue)	Fuel costs (% costs[d])
Tiger prawn, NPF (CW)[a]	9,685	30.0	45.1	
Rock lobster, southern zone (SA)	6,650	20.6	9.3	19.7
Rock lobster, northern zone (SA)	5,742	17.8	9.7	18.7
Torres Strait prawn (CW)	5,300	16.4	46.0	51.1
Ocean prawn fishery (NSW)	4,147	12.9	15.8	29.3
Tasmanian rock lobster (TAS)	3,608	11.2	5.8	18.7
All prawns, NPF (CW)	3,465	10.7	26.1	39.7
Spencer Gulf West Coast prawn (SA)	2,092	6.5	11.1	20.8
Southern/western tuna (CW)	1,986	6.2	11.9	18.7
Banana prawn, NPF (CW)[a]	1,610	5.0	14.7	
Gulf St. Vincent prawn (SA)	1,503	4.7	9.8	19.8
Ocean trap and line fishery (NSW)	1,319	4.1	11.1	16.6
Abalone (NSW)	1,203	3.7	1.4	3.4
SE finfish, offshore trawl (CW)[b]	1,091	3.4	21.5	31.1
SE finfish, inshore trawl (CW)[b]	1,088	3.4	21.5	29.2
Eastern tuna (CW)	1,023	3.2	14.2	23.0
Blue crab (SA)	1,000	3.1	10.1	21.7
SE finfish, all trawl (CW)[b]	907	2.8	20.0	33.0
Abalone (TAS)	878	2.7	2.3	14.6
Southern shark (CW)	873	2.7	8.2	12.7
Abalone (SA)	809	2.5	1.8	5.6
SE finfish, all gears (CW)[b]	788	2.4	17.4	29.5
Estuary general fishery (NSW)	549	1.7	6.2	6.3
SE finfish, Danish seine (CW)	316	1.0	6.9	13.1
Small pelagics (TAS)[c]	164	0.5		
Sardines (SA)	92	0.3	12.0	22.3

[a]Expenditure data could not be divided between fishing seasons

[b]ABARES survey results differentiated between inshore and offshore trawl until 2002. Total trawl and total SE whitefish values here are for 2008-09 to 2010-11, while inshore and offshore values are for 1999-00 to 2001-02

[c]Revenue calculated based on beach price of Australian sardine fishery, assuming similar value

[d]Fuel costs as a percentage of a subset of variable fishing costs, including labour, repairs and maintenance, and bait

CW = Commonwealth, **SA** = South Australia, **TAS** = Tasmania, **NSW** = New South Wales.

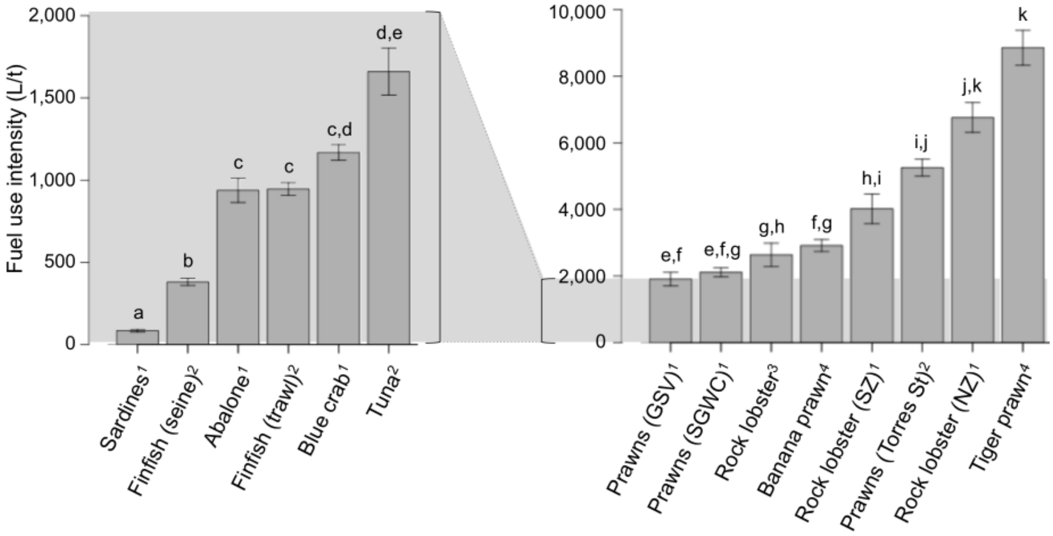

Figure 4.3. Fuel use intensities of selected Australian fisheries, showing mean and standard error. Common letters indicate fisheries with FUIs which are not significantly different. Note the difference in y-axis values between less and more energy intensive fisheries.
[1]South Australia; [2]Commonwealth-managed; [3]Tasmania; [4]Different seasons of the Northern Prawn Fishery (Commonwealth)

molluscan dive fishery for abalone was an exception to this, as abalone has a much higher price per kg than prawn and tuna fisheries but a relatively lower FUI.

Fisheries also varied in their FUI depending on gear used. The small pelagic trawl fishery in Tasmania, for example, was more fuel intensive than the seine fishery for sardines in South Australia. Similarly, seining vessels in the Southeast finfish fishery consumed on average a third the fuel per tonne as their trawling counterparts. Very little difference in FUI was found between finfish trawlers operating in the inshore and offshore fisheries (Table 4.2).

The proportion of revenue directed to purchase of fuel in Australian fisheries also varied widely, with less than 3% of revenue in abalone fisheries used to purchase fuel, while over 40% of revenue in fisheries for Tiger prawns was spent on fuel (Table 4.2). Similarly, fuel accounted for between 3% and 51% of the subset of variable fishing expenditures assessed.

The profitability of Australian fisheries was tied to price of fuel based on percentage of revenue devoted to purchasing fuel. The relationship between the price of diesel and fuel costs was significant in all 14 fisheries, while the relationship between FUI and fuel costs was significant in 13 of 14 fisheries. For most fisheries (12 of 14), the price of diesel had more influence on the economic role of fuel costs than fuel consumption rates, although both were highly significant.

Rates of fuel consumption and fuel costs as a percentage of revenue were relatively consistent during the 1990s, but increased in many fisheries in the early years of the

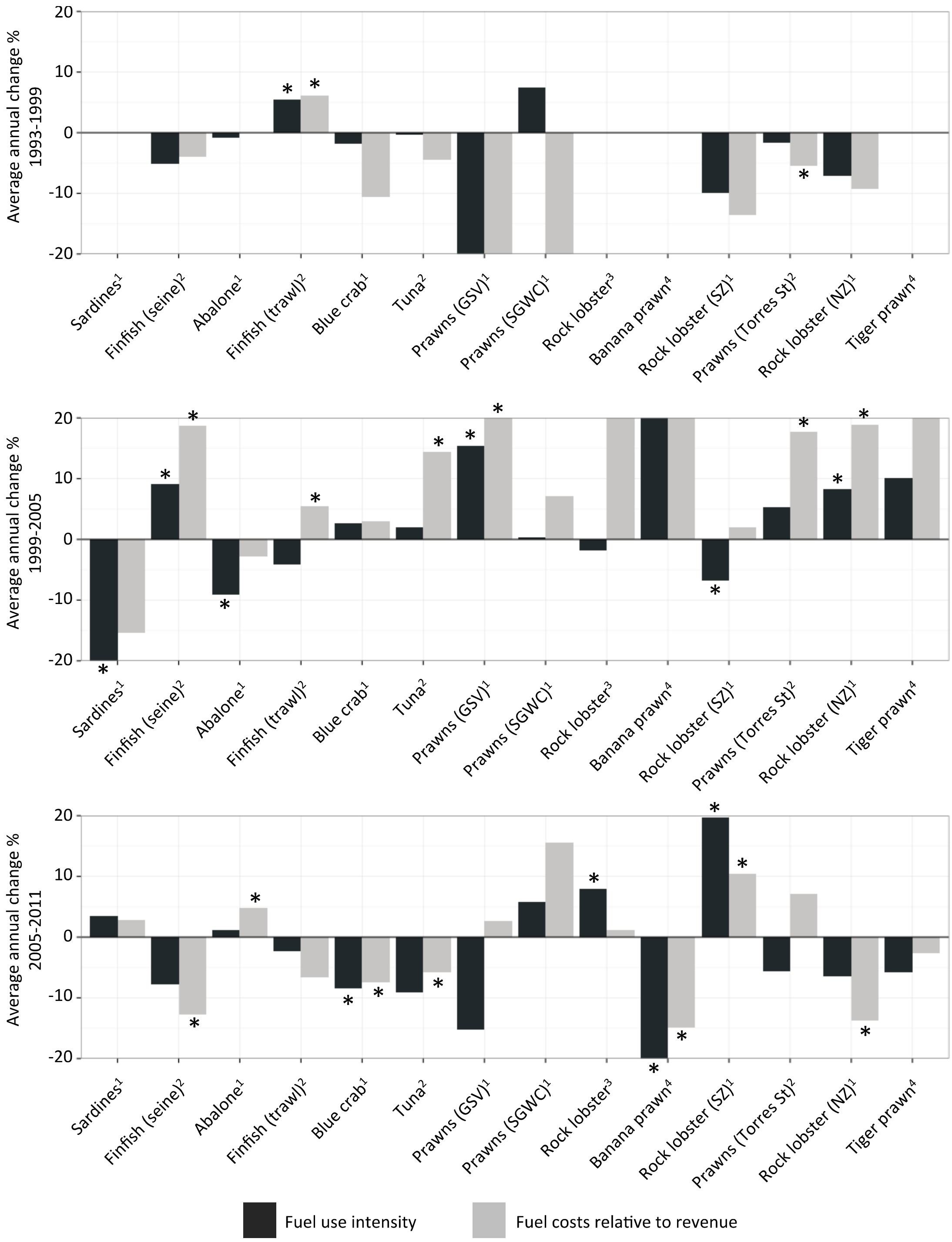

Figure 4.4. Average annual change in FUI and fuel costs relative to revenue in Australian fisheries over three time periods: 1993-1999, 1999-2005, and 2005-2011. Asterisks represent significant trends based on regression slope of fuel use and costs against year. Fishery jurisdictions are indicated by superscript: [1]South Australia, [2]Federal, [3]Tasmania, [4]Northern prawn fishery (federal). See Appendix C for yearly FUI and fuel cost data.

21st century (Figure 4.4). Between 1999 and 2005, 9 of 14 fisheries showed increasing rates of fuel consumption while 12 of 14 fisheries showed increasing rates of fuel costs. Since 2005, the trend of increasing fuel use and costs had reversed somewhat, with 9 of 12 fisheries demonstrating a decreasing trend in FUI and 7 of 14 fisheries decreasing their fuel costs. There was a relatively consistent coupling of FUI and fuel costs relative to revenue, in that fisheries with increasing FUI tended to have increasing fuel costs, and vice versa. The economic role of fuel costs, however, tended to increase and decrease more quickly than did actual consumption (Figure 4.4).

While both FUI and fuel costs improved in recent years in many fisheries, most Australian fisheries still currently spend more on fuel relative to their revenue than they did in the 1990s and early 2000s. This was despite the trend of many Australian fisheries generally consuming similar amounts of fuel or decreasing their fuel consumption over the same period. This lower consumption of fuel in response to increasing fuel costs was most evident in fuel intensive prawn fisheries. Falling ex-vessel prices in certain fisheries further exacerbated the rising cost of fuel relative to fishing revenue.

4.5 Discussion

4.5.1 Rates of fuel use in Australian fisheries

The role played by fuel consumption in Australian fisheries varied significantly between fisheries, in terms of absolute consumption, related carbon footprint, and operational costs. Furthermore, fuel consumption and the impact of fuel costs have changed markedly since the 1990s, during a period when the price of diesel to fishermen increased fourfold. This economic impact of fuel costs was greatest across all fisheries in the early years of the 21st century. Interestingly, that impact has lessened somewhat in recent years.

Fisheries examined here were substantially more fuel intensive than most fisheries around the world. The globally averaged FUI of fisheries in 2000 was estimated at 620 L/t (Tyedmers *et al.*, 2005), while the median value of documented FUIs since 1990 is a similar 625 L/t (Parker and Tyedmers, 2015). All but four of the assessed fisheries here have a higher FUI than global averages. This is due to the large proportion of fisheries in Australia targeting fuel-intensive crustaceans. Even when compared on the basis of similar species and gears, however, Australian fisheries tend to demand more energy inputs. Trap fisheries for American lobster (*Homarus americanus*), and Norway lobster (*Nephrops norvegicus*), consume approximately 1,000 L/t (Boyd, 2008; Driscoll, 2008) and 2,200 L/t (Ziegler and Valentinsson, 2008), respectively, compared to the Australian lobster FUI averages of 3,600-6,650 L/t found here. Similarly, European trawl fisheries for Atlantic cod (*Gadus morhua*) and other whitefish species generally consume 300-600 L/t, lower than Australia's finfish fisheries (Tyedmers, 2001; Ziegler *et al.*, 2003). Some of these differences are likely explained by differences in local productivity and biomass: Australian lobster fisheries, for example, target species with relatively lower biomass density than those in North America.

The relationship found in Australian fisheries between FUI, target species and gear type reflect those found previously in other regions. Fuel use intensity values documented in the North Atlantic and Europe show a clear pattern of crustacean and demersal fisheries consuming greater amounts of fuel than fisheries targeting pelagic finfish and small pelagic species (Schau *et al.*, 2009; Tyedmers, 2001). These studies also found that trawl fisheries were more intensive than seine fisheries targeting the same species, as was found here for Australian whitefish and small pelagic fisheries.

An important relationship between fuel costs and ex-vessel prices was apparent across the industry. Fisheries with higher value products, such as lobster, were found to have higher rates of fuel consumption. High prices allow for much higher rates of fuel use than would otherwise be viable. Furthermore, if ex-vessel prices increase faster than the price of fuel, then some Australian fisheries that are currently limited by fuel costs will become viable and could increase production.

4.5.2 Decreased FUI in response to biomass and capacity changes

Observed improvements in fishery fuel use could be related to changes in management, stock levels, fishing behaviour, or technology. The relative impact of each of these factors varies. While much work has been done regarding the potential fuel benefits of new technologies and vessel designs, these changes often improve rates of fuel use by only a small fraction. Options such as optimizing propeller diameter, installing fuel meters, and implementing minor gear improvements, while often suggested as ways to decrease fuel consumption, typically only result in less than a 10% improvement (OECD, 2012). Operational changes, notably decreasing vessel speed, have been shown to be more effective, and are a relatively quick adaptation to higher prices (Abernethy *et al.*, 2010). However, the largest changes in fuel performance have often been attributed to management decisions, particularly those that affect levels of biomass or fishing capacity (OECD, 2012, Parker and Tyedmers, 2015). Decreases in the FUI of the Banana prawn fishery in Australia, for example, coincided with a government buyout of vessels to rapidly reduce over-capacity since 2005 (Pascoe *et al.*, 2012). Fuel use in the South Australian southern zone fishery for Southern rock lobster, meanwhile, closely correlate with noticeable changes in catch per unit effort: both fell prior to 2005, increased from 2006 to 2010, and fell again in 2011 (Linnane *et al.*, 2012).

Observed changes in energy performance in accordance with changes in biomass and fishing capacity have been reflected in other fisheries around the world. Swedish fisheries for lobster (*Nephrops norvegicus*) and cod (*Gadus morhua*) underwent noticeable improvements in FUI as a result of reductions in capacity and increased biomass, respectively (Ziegler and Hornborg, 2014). Poor management and stock decline, meanwhile, may explain increased FUI in Indian Ocean tuna fisheries in recent years (Parker *et al.*, 2015b). Fisheries elsewhere are also experiencing similar economic impacts from rising fuel prices: European fisheries are dedicating consistently larger portions of their revenue to purchasing fuel while their FUI remains steady or improves (Anderson and Guillen, 2011; Parker and Tyedmers, 2015). Findings here complement evidence from Europe and North America that changes in biomass and capacity have a greater impact on fuel use than technological or behavioural changes (Mitchell and Cleveland, 1993; Parker and Tyedmers, 2015; Ziegler and Hornborg, 2014).

4.5.3 Carbon footprints and carbon taxes

Measurements of the carbon footprint of fisheries and other production systems increasingly call for a life cycle assessment (LCA), where energy and material flows are measured from "from cradle to grave" including upstream and downstream activities (*e.g.* processing, transport) (BSI, 2012; Pelletier and Tyedmers, 2008). A range of LCA studies have been conducted on seafood products, although applications in Australia have taken place only very recently, while most work has been undertaken in Europe (Parker, 2012; Vázquez-Rowe *et al.*, 2013; Avadí and Fréon, 2014). While the characteristics of these fisheries vary substantially, from high-volume, low-value fisheries for small pelagic species (*e.g.* Almeida *et al.*, 2014, Avadí *et al.*, 2014), to low-volume, high-value fisheries for crustaceans (*e.g.* Ziegler and Valentinsson, 2008; Farmery *et al.*, 2014), fuel is consistently found to accounts for a large portion, and often the vast majority, of life cycle GHG emissions. fuel consumption can generally be used as a proxy for fishery carbon footprints, allowing for reasonable estimates without the time and effort required for a full LCA study (Parker and Tyedmers, 2015).

For many fisheries assessed in this study, fuel is likely the primary driver of life cycle emissions; however, there are upstream and downstream sources of emissions likely to significantly affect the carbon footprint in some cases. Fisheries for rock lobster require bait and their products are often transported by air, which accounts for a significant portion of the life cycle emissions of crustacean products (Boyd, 2008; Driscoll, 2008; Parker, 2012). Air transport is especially significant, and approximately doubles the carbon footprint, of exported Australian lobster (Farmery *et al.*, 2014; van Putten *et al.*, *in press*). Other potential sources of GHG emissions in fisheries-derived products include energy-intensive processing (Parker and Tyedmers, 2013), addition of energy-intensive ingredients such as oil in canned fish (Buchspies *et al.*, 2011), and product loss and waste along the supply chain (Thrane *et al.*, 2009).

The Australian government enacted a carbon tax 2012, which was subsequently repealed in 2014. Transport and agriculture sectors, including fisheries, were exempted from the tax. In fact, Australian fisheries, like those in many countries, benefit from rebate of a fuel excise, which is otherwise used to fund the national highway system. This reduces the cost of fuel relative to many other industries. Very few countries have an effective carbon control mechanism that includes fisheries. Most policies, such as those in the European Union, Japan, and Australia, exempt fisheries from carbon taxes. New Zealand put a carbon trading scheme in place in 2008 and amended it in 2010 to include fisheries, while Norway has a relatively modest carbon tax on fishers of 50 kr (US$8.40) per tonne of GHG.

The potential effects of a carbon tax or other carbon control mechanism on fisheries could have both desirable and undesirable consequences. In one respect, the increased fuel cost associated with such a policy could spur efficiency improvements, force removal of inefficient vessels from fishing fleets, and provide a competitive advantage to those fisheries with better energy performance. This potential improvement is similar to that modeled in European fisheries over the long term in response to increased oil prices (Arnason, 2007), and the results here suggest that at least some Australian fisheries do have the capability to respond to increased costs by decreased fuel consumption.

There is, however, a possible negative side effect of the use of a carbon price to reduce fuel consumption in fisheries. Most fishery products globally, particularly non-crustacean products, are less energy- and carbon-intensive than land-based protein products (Pelletier *et al.*, 2011; Pimentel and Pimentel, 2003; Tyedmers *et al.*, 2005). Ruminant-based agriculture in particular tends to have comparatively higher GHG emissions from feed production and methane emissions (Sonesson *et al.*, 2010). Production of fisheries in many countries is sensitive to costs of fuel, such as where they are managed for maximum economic yield or where hey are marginally profitable because of low prices. If carbon pricing resulted in higher fuel costs, and therefore decreased fisheries production, a shift towards more carbon intensive land-based sources would raise overall GHG emissions. Further, while many more intensive fisheries have some room for improvement as demonstrated here, the less fuel-intensive fisheries – particularly some lower value finfish and small pelagic fisheries that have very low GHG emissions – may actually be more impacted by the increased cost. Hence, this indirect effect of carbon pricing could have the inverse effect of that intended.

4.5.4 Applications to other regions

It is important to consider the extent to which findings here can be applied to diverse fisheries around the world, particularly in regions where fisheries contribute substantially to food security or economic activity. Compared to many regions, Australian fisheries are unique in their relatively high average beach price, high rates of investment to technology, research and management, and strict quota-based management systems. High prices and management funding place Australia in a position of flexibility to, for example, develop and adopt new technologies or transition to more effective regulatory measures, compared to poorer countries or countries fishing less valuable species.

High seafood prices also place Australian fisheries in an interesting situation where the price is often high enough to compensate for rising costs. This translates to a weaker incentive to improve fuel performance at times when prices are high. Conversely, in regions where beach prices are generally much lower, and particularly in developing countries where fuel accounts for a large percentage of variable fishing costs, the economic benefits of improving performance are likely to be greater and more necessary as oil prices rise.

The economic incentive for management decisions that contribute to fuel use reductions is likely to be greatest in areas where CPUE is low due to depressed stocks or over-capacity. Arnason (2007) modeled how economic performance of fisheries in these regions would benefit in the long term from high oil prices driving down capacity and fishing activity in the short term, allowing for stocks to rebound and removing the least efficient vessels from the fleet. Regulatory controls such as those undertaken in some Australian fisheries can be expected to have the same long-term impact, building industry resilience to oil price increases rather than responding to them.

4.6 Conclusions

Fisheries are facing a wide range of sustainability challenges, and diverse management efforts are developing globally to address them. Fuel consumption, and the associated carbon footprint, of fisheries is a relatively new addition to this suite of challenges, and is yet to be formally incorporated into fishery policies and regulations. There is, however, interest on the part of industry groups, NGOs, and other stakeholders to address the challenge by measuring, characterizing and improving fuel use (Parker and Tyedmers, 2015).

Globally, fisheries perform favourably to many other form of protein production. Crustacean fisheries are the least efficient, and have similar carbon emissions during production to beef. Finfish fisheries, and especially small pelagics, on the other hand, are often associated with lower emissions during production than chicken, pork or farmed salmon (Parker and Tyedmers, 2015). Measuring and improving the carbon footprint of fisheries, then, could be a market advantage for fisheries products, provided that those fisheries also meet other sustainability standards.

Demonstrating the economic benefits of management decisions via improved variable fishing costs and resilience to oil prices can be a valuable tool for encouraging implementation of fisheries management decisions. Australian examples provided here illustrate the extent to which management-driven changes in biomass and capacity can effectively improve fuel consumption, carbon footprint, and fishing costs. It is important that the issue of fuel performance be considered by fishing industries now, as improving performance before further increases in prices is likely to increase resilience. In these efforts, it does more to focus on management efforts to decrease over-capacity and rebuild stocks, than to rely on technology improvements.

Chapter 5. Energy performance of rock lobster fisheries

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5.1 Abstract

Consumption of diesel fuel is a leading cost to fishers and the primary source of greenhouse gas emissions from the global fishing industry. There is substantial variation in fuel use between and within fisheries. However, the drivers behind differences in fuel use are unclear and inconsistent across studies. We surveyed rock lobster fishers in Australia and New Zealand to measure their rates of fuel use and assess the relative influence of factors: technological (vessel size, engine power), behavioural (distance travelled, speed), and managerial (catch per unit effort, fishery capacity). Fuel use intensity (L/t), as well as most vessel and fishery characteristics, varied significantly between fishing locations. The average fuel consumed to catch and land rock lobster, weighted by regional production, was 1,890 L/t. Factors influencing fuel use in rock lobster fisheries varied between sectors of the industry: managerial factors were more important in single day trips and technological factors heavily influenced multiday trips. Catch per unit effort was the only significant driver

present across both types of fishing trips. The vast majority of surveyed fishers identified fuel use as an important aspect of fishing operations, and nearly half had already implemented changes to try to reduce consumption. Our results suggest that efforts to reduce fuel consumption, costs, and emissions in fisheries need to be tailored to the nature of the individual fishery, as the relative roles of technology, behaviour, and management vary.

5.2 Introduction

Commercial fishing in marine environments is often an energy-intensive activity (Pelletier *et al.*, 2011; Tyedmers, 2004). As such, fisheries contribute to depletion of energy resources and, more pertinently, climate change via emissions of greenhouse gases (GHGs). Diesel fuel is a major cost to fishers and an important consideration in the sustainability of fishing communities and ocean-based economies, and is the primary driver of GHGs from marine capture fisheries. Inputs of diesel fuel are required to propel the vessel, operate gear, run refrigeration and other onboard operations, power onboard processing, and generate electricity for lights, sonar, and other services. As a result, fuel is the largest operating cost to fisheries after labour, accounting for 20 to 40% of operating expenses (FAO, 2007; Lam *et al.*, 2011). Globally, fuel inputs to fisheries – in terms of litres burned per tonne of fish landed at the dock – vary between sectors by as much as three orders of magnitude, depending on the species being targeted and the fishing gear being used (Parker and Tyedmers, 2015). The resulting carbon dioxide (CO_2) emissions from fisheries range from amongst the most efficient means to source animal protein—for small pelagic forage fish—to amongst the more carbon-intensive systems, with some crustacean and flatfish fisheries emitting as much as land-based production of beef and lamb.

Rates of fuel use have substantial environmental, economic, and social implications with regards to fishing operations, products and supply chains, and the viability and resilience of fishing communities. Tyedmers *et al.* (2005) estimated that globally in 2000, the world's wild-capture marine fisheries consumed 50 billion litres of diesel fuel. Consequently they produced 130 million tonnes of carbon dioxide-equivalent (CO_2-eq) greenhouse gas (GHG) emissions—equal to the carbon footprint of the Netherlands. Fuel-related emissions, including upstream mining, refining and transport of oil, typically account for between 60 and 90% of the total life cycle emissions of fisheries-derived products (Parker, 2012). Emissions associated with animal protein production, from fisheries, aquaculture, and agriculture, account for a large portion of global GHG emissions, and adapting diets remains a major option for individuals to reduce their personal emissions (Carlsson-Kanyama, 1998; Tilman and Clark, 2014). In addition to the environmental significance, fuel costs in fisheries also have a large impact on food security and economic security of fishing communities (Abernethy *et al.*, 2010). This impact is particularly important in developing countries where fish make up a relatively larger source of protein, fuel costs account for a larger share of total operating costs and there is less capacity to adapt to rising prices (Pelletier *et al.*, 2014).

Rock lobsters can be found on most coasts of Australia and New Zealand, with the most commercially significant species being Western rock lobster (WRL; *Panulirus cygnus*), Southern rock lobster (SRL; *Jasus edwardsii*), Eastern rock lobster (*Sagmariasus verreauxi*) and Tropical rock lobster (TRL; *Panulirus ornatus*) (Figure 5.1). With the exception of dive fisheries for Tropical rock lobster, commercial fisheries for rock lobsters employ pots or traps, with vessels typically operating between 50 and 150 pots depending on jurisdiction. Fisheries for all Australian rock lobster fisheries, with the exception of the Torres Strait TRL fishery, are managed using individual transferable quotas. All are currently considered to be sustainably fished (Flood *et al.*, 2014), and the fishery for WRL has been certified by the Marine Stewardship Council as sustainably managed. In 2012-13, there were a total of 1,051 rock lobster fishery license holders or shareholders in Australia and 437 in New Zealand. Of those, 826 and 255 were actively fishing in Australia and New Zealand, respectively (Table 5.1).

Rock lobster fisheries make up the most valuable sector of Australia's wild-caught fishing industry. In 2012/13, the Australian and New Zealand industries landed approximately 10,500 and 2,800 t of rock lobsters, respectively. While comprising a relatively small percentage of overall fishery landings by volume, rock lobsters account for 30% of the gross value of Australian fisheries production and 40% of fisheries export value (Skirtun *et al.*, 2012). The vast majority of landed rock lobsters from Australia and New Zealand are destined for live export, primarily to the Chinese market. Average ex-vessel prices in recent years have ranged from US$ 50-100 per kg.

Fuel consumption in Australian rock lobster fisheries has previously been estimated based on expenditure and revenue surveys for South Australia and Tasmania (Parker *et al.*, 2015a), which identified rock lobster fisheries as amongst the most fuel-intensive fisheries in Australia, along with other crustacean fisheries. The cost of fuel as a percentage of revenue and total costs, however, was found to be relatively lower in rock lobster fisheries, suggesting that the high value of rock lobster products

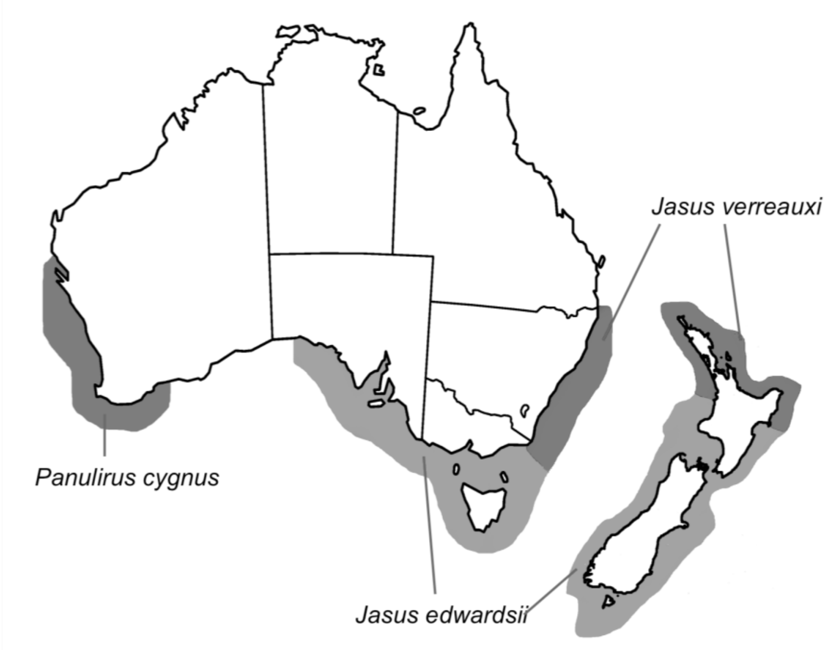

Figure 5.1. Distribution of commercial trap fisheries for rock lobsters in Australia and New Zealand

Table 5.1. Characteristics of commercial Australian and New Zealand rock lobster fisheries included in analysis by locale.

Region	**Tasmania**	**Western Australia**	**South Australia NZ**	**South Australia SZ**	**New South Wales**	**New Zealand**
Primary species	*Jasus edwardsii*	*Panulirus cygnus*	*Jasus edwardsii*	*Jasus edwardsii*	*Sagmariasus verreauxi*	*Jasus edwardsii*
TACC (t)[a]	1,103	5,500	345	1,250	140	2,797
Licenses[b]	311	274	68	181	101	437
Active vessels[a]	212	273	48	164	82	255
Primary trip type (days)	Single/ multi	Single	Multi	Single	Single	Single/ multi

[a]Total allowable commercial catch and number of actively fishing vessels for 2012/13 fishing year, sourced from regional fishery assessment reports. Tasmanian TACC for 2014/2015 year has been reduced to 1,051 t.
[b]Total fishery licenses or number of shareholders sourced from regional assessments (New Zealand Rock Lobster Industry Council, 2014; Stephan and Hobsbawn, 2014).

compensated for the high inputs. Farmery *et al.* (2014) assessed the energy use and emissions associated with Tasmanian rock lobster products, and modeled the potential effect of management changes: they suggested the combination of transitioning from maximum sustainable yield to maximum economic yield and removing limits on the number of pots per vessel could drastically improve the fuel performance of the fishery.

While species and gear differences can explain variation in fuel use across diverse fisheries, both globally and within Australia (Parker *et al.*, 2015a; Parker and Tyedmers, 2015), it is less clear what drives variation between vessels within a fishery, or between fisheries targeting similar species with the same gear but in different locations. Numerous studies have identified a range of variables which may influence fuel use, and have suggested that changing these variables could have dramatic effects on the fuel performance of individual vessels and fleets. However, results vary between studies and correlations are not consistent between fisheries. Here we investigate the individual drivers of fuel consumption in rock lobster fisheries to determine what variables—technological, behavioural, and managerial—have the greatest influence on energy performance and consequently GHG emissions.

The objectives of this paper are three-fold. First, the fuel use intensity (FUI), measured as litres of fuel per tonne of landings (L/t), is calculated and compared across a diverse set of rock lobster trap fisheries in Australia and New Zealand. Second, the FUI of fishing vessels and the average fuel performance of each region are assessed in relation to a suite of technological, behavioural, and managerial variables. Finally, those variables are tested to determine if fuel performance of rock lobster fishing vessels can be predicted based on a subset of fishery characteristics, and therefore if control over those variables could potentially be used as a method to decrease fuel consumption, operating costs, and carbon emissions in the industry.

5.3 Methods

Surveys were distributed to fishers in five Australian rock lobster fisheries (Western Australia, southern and northern zones of South Australia, Tasmania, and New South Wales) as well as New Zealand, all operating with traps and targeting three distinct species of rock lobster (Table 5.1). Mail and email lists were obtained from government and industry organizations in each region, and surveys were distributed in collaboration with industry partners.

Surveys included questions on the vessel (length, horsepower, engine efficiency), operations (number of days fished, number of pots, inputs of bait and fuel), trip characteristics (days per trip, distance to fishing grounds), and production (landings of lobster and non-lobster species) in the 2012-2013 fishing year. Respondents were also asked how important fuel use was to their operations, if they had made any operational or behavioural changes in response to the cost of fuel, and how they expected fuel use and costs to affect their operations over the next five years (see survey and cover letter in Appendix D).

Returned surveys that did not provide enough information for analysis, and those that reported more than 25% of their catch from non-lobster species, were excluded from analysis.

FUI of each vessel was calculated from total fuel consumption and total round weight landings in the 2012-2013 fishing year. Where direct fuel consumption was not reported, consumption was estimated based on yearly fuel expenditure and average diesel price, and/or per-trip fuel consumption and number of trips.

Variables of interest from returned surveys were divided into three categories to test their relationship to FUI. These included technological factors (length, HP, engine efficiency, and specific fuel consumption), behavioural factors (trip length, trip distance, reported level of fuel importance, and reported changes to operations), and managerial factors (number of pots, catch per unit effort, and fishery capacity) (Table 5.2). Numbers of pots per vessel and fishery capacity (number of vessels and pots in the fleet relative to TACC) were considered management variables because they were directly controllable through regulations in each fishery. Likewise, CPUE and biomass were considered management variables because they were indirect results of historical management decisions made regarding TACC.

Multiple regression analysis was used to investigate factors that influence FUI. The analysis was conducted for all fishing trips combined, all trips undertaken in a single day, and all trips lasting multiple days. In each case a Box-Cox analysis indicated that a log transform was appropriate and examination of residual plots further supported the suitability of this model. Insignificant variables were removed sequentially in order of least significance from the fully saturated model (without interaction terms) until only significantly related variables remained in each model.

Table 5.2. Variables included in analysis of fuel use intensity relationships, separated by technology, behaviour, and management categories.

Category	**Variable**	**Unit**	**Source**
Technology	Vessel length	m	Survey
	Vessel horsepower	HP	Survey
	Engine efficiency	L/hr	Survey
	Specific fuel consumption	mg/HP/hr	Calculated from survey
Behaviour	Trip length	Days	Survey
	Distance to fishing grounds	km	Survey
	Average trip speed	km/hr	Calculated from survey[a]
	Stated level of importance of fuel	1-5	Survey
	Stated operational and behavioural changes	Yes/No	Survey
Management	CPUE	kg/potlift	Calculated from survey
	Number of pots	pots	Survey
	Fishery capacity	vessels/1000 t TACC	Management and assessment reports
	Fishery capacity	pots/tonne TACC	Management and assessment reports; survey

[a]Average trip speed was calculated based on the total distance to and from fishing grounds as well as the total distance within fishing grounds while fishing, as well as the number of hours per trip. Average trip speed was not calculated for multiday trips.

5.4 Results

A total of 81 completed surveys were returned. Regionally, 27 surveys were returned from South Australia, 20 from Tasmania, 16 from Western Australia, 11 from New Zealand, and six from New South Wales. Five surveys were removed from analysis due to incomplete data, and six were removed because rock lobster made up less than 75% of their catch, leaving a total sample size of 70 vessels.

Vessels varied between and within regions with regard to vessel size, operations, and production (Table 5.3). Technologically, fisheries ranged from smaller vessels with smaller, less fuel-intensive engines in Tasmania, New South Wales and New Zealand, to larger vessels with more fuel-intensive engines in Western Australia. Vessel length ranged from 5 to 25 m, with a total average length across all regions of 14 m, and engine horsepower ranged from 50 to 1,600 with an overall average of 552. Operations in Tasmania and the northern zone of South Australia were characterized by multiday trips and greater distances to fishing grounds, while trips were shorter and conducted in a single day in Western Australia, New South Wales, and the southern zone of South Australia. Catch per unit effort ranged from 0.3 to 5.5 kg/potlift, with an average across all regions of 1.4 kg/potlift.

Fuel costs were identified as "important" or "very important" by 82% of respondents and 41% had changed operations in response, including by reducing distance to fishing grounds (19%), being more selective of fishing days (14%), reducing speed (14%), and installing smaller or more efficient engines (7%). Generally, fishers reporting higher fuel costs were more likely to consider fuel an important or very important factor in their operations (Figure 5.2).

Table 5.3. Characteristics of surveyed rock lobster fishing vessels, mean ± standard error.

Region	Tasmania	Western Australia	South Australia NZ	South Australia SZ	New South Wales	New Zealand	All
Sample size	19	15	7	17	4	8	70
TECHNOLOGY							
Vessel length (m)	15.3 ±0.8	16.4 ±0.5	16.1 ±0.7	14.4 ±0.3	9.3 ±3.0	9.8 ±1.2	14.4 ±0.4
Vessel HP	342 ±48	885 ±73	401 ±101	689 ±35	335 ±164	376 ±65	552 ±37
Engine fuel use (L/hr)	17.3 ±2.4	73.8 ±9.0	30.1 ±5.2	55.5 ±5.1	25.0 ±9.8	37.6 ±14.5	42.6 ±3.9
Spec fuel cons (mg/kWs)	9.8 ±0.8	14.9 ±1.5	15.3 ±2.2	13.9 ±1.1	16.8 ±4.9	14.9 ±3.1	13.4 ±0.7
BEHAVIOUR							
Days per trip	8 ±1.3	1 ±0.1	5 ±0.6	1 ±0	1 ±0	2 ±0.7	3 ±0.5
Average speed (km/hr)[a]	5.4 ±1.2	7.9 ±1.5		11.7 ±1.3	11.9 ±2.2	15.2 ±7.4	10.2 ±1.2
Distance to fishing (km)	80.6 ±16.7	19.2 ±3.1	48.0 ±14.6	25.3 ±3.7	28.3 ±7.3	32.5 ±17.3	42.8 ±6.2
Importance of fuel 1-5	3.9 ±0.2	4.1 ±0.2	4.6 ±0.3	4.5 ±0.2	4.7 ±0.3	3.9 ±0.4	4.2 ±0.1
% that have adapted operations	35%	42%	80%	36%	67%	25%	41%
MANAGEMENT							
Number of pots	47 ±1.3	157 ±27.7	72 ±3.2	79 ±3.5	88 ±47.1	121 ±7.9	92 ±8.0
CPUE (kg/potlift)	0.9 ±0.1	2.3 ±0.3	1.2 ±0.1	1.0 ±0.1	1.0 ±0.4	2.0 ±0.7	1.4 ±0.1
Vessels per 1000t TACC[b]	192	50	139	131	586	91	
Pots per t TACC[b]	9.0	7.8	10.0	10.4	51.3	11.1	
FUI (L/t)	2,333 ±367	1,722 ±197	2,438 ±306	3,219 ±232	3,067 ±838	1,329 ±274	2,355 ±154

[a]Average speed calculated only for single day trips based on total distance to, from, and within fishing grounds, and number of hours per trip.
[b]Total allowable commercial catch and number of actively fishing vessels sources from regional fishery assessment reports.

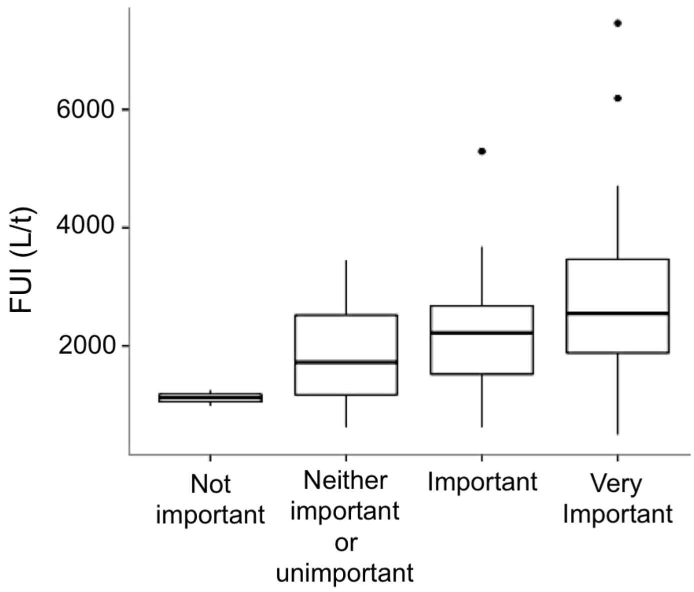

Figure 5.2. Importance of fuel use and fuel costs to fishing operations, as reported by rock lobster fishers, with distribution of FUI corresponding to each response. No fishers considered fuel use to be “very unimportant”.

Average FUI of all vessels was 2,355 L/t with a standard deviation of 1,289 L/t. The lowest reported FUI was 498 and the highest was 7,462. Weighted by each region's production, the average FUI of landed rock lobster was 1,890 L/t. Rates of fuel use were lowest in New Zealand and Western Australia, and seven of the ten vessels with the lowest FUI were from those regions. Variation in FUI between regions was statistically significant (64 and 5 DF, p=0.002) (Figure 5.3).

Multiple regression models of rock lobster vessels operating single day and multi-day trips identified different predicting variables, with a combination of managerial and technological factors significantly contributing to both (Figure 5.4). Across all fishing trips combined, FUI was significantly related to CPUE, engine HP, number of fishing vessels per unit TACC, and vessel length (Table 5.4). FUI of vessels undertaking single day trips was most influenced by managerial factors, with significant relationships to CPUE, engine efficiency, and number of pots per vessel. FUI of vessels operating multiday trips was more heavily influenced by technological variables, with significant relationships to engine HP, vessel length, and CPUE. The magnitude and direction of predictive relationships between independent variables and FUI for each sector are displayed in Table 5.5 and Figure 5.4. The only factor identified as a significant driver of FUI in both single day and multiday trips was CPUE: modeled decreases in FUI of approximately 20% per kg increase in CPUE were found in each sector. A stronger predictive power of the model was found for multi-day trips (r_2=0.78) than for single day trips (r_2=0.55) (Figure 5.5).

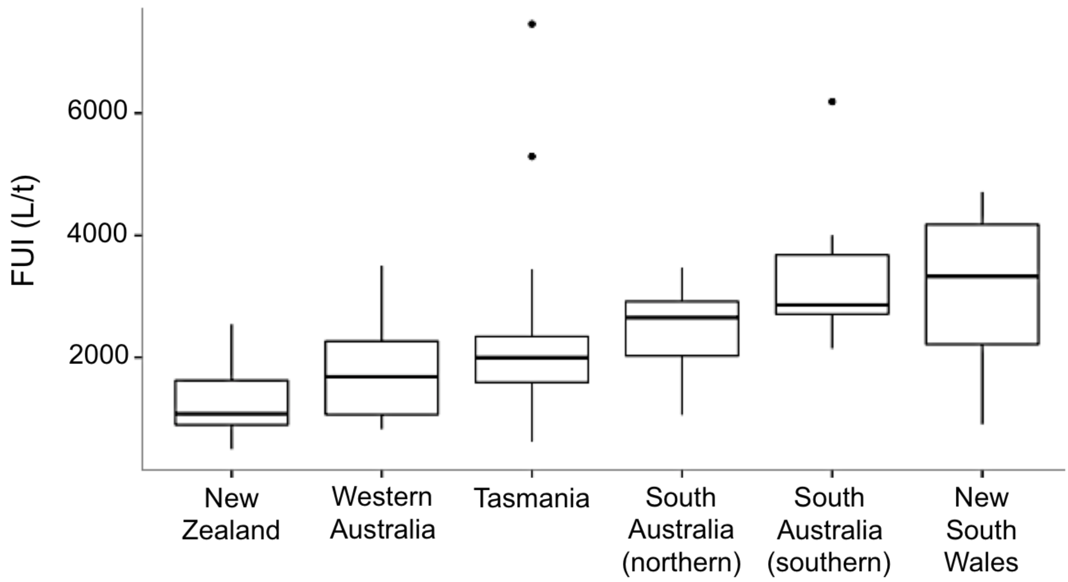

Figure 5.3. Tukey boxplot distribution of rock lobster vessel fuel use intensity (L/t) by location. Centre line shows median value, box encompasses 50% of values, extending lines encompass all remaining values except outliers (points).

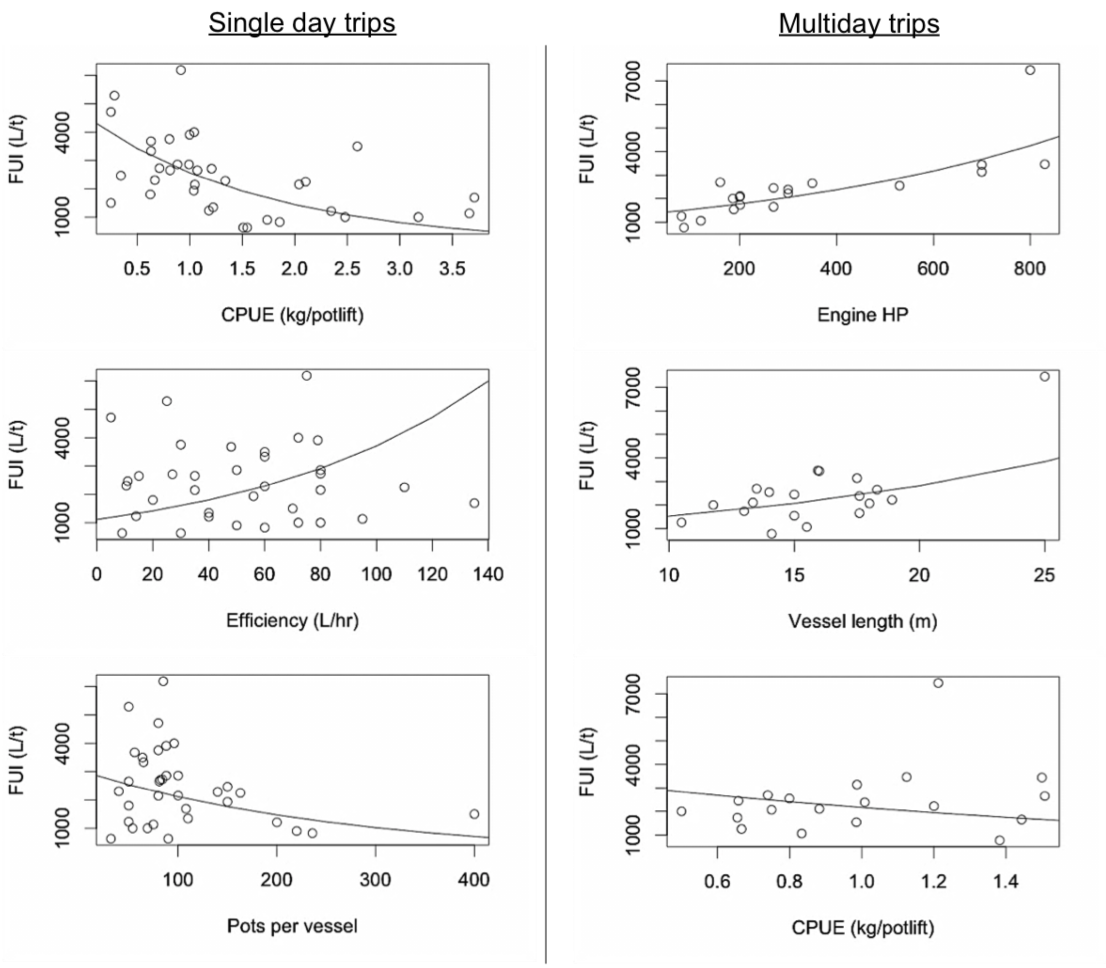

Figure 5.4. Relationship between fuel use intensity and significant variables for both single day and multiday rock lobster fishing trips. Regression lines display relationship for each independent variable from multiple regression analysis, holding other significant variables constant at their mean values.

Table 5.4. Relationship between independent variables and fuel use intensity in rock lobster fishing trips, in decreasing order of significance. Statistically significant relationships, as found in multiple regression analysis, are marked with an asterisk.

All trips		**Single day trips**		**Multiday trips**	
Variable	**P[a]**	**Variable**	**P[a]**	**Variable**	**P[a]**
CPUE	<0.01 *	CPUE	<0.01 *	Engine HP	<0.01 *
Engine HP	<0.01 *	Efficiency (L/hr)	<0.01 *	Vessel length	0.02 *
Fishing capacity	<0.01 *	Pots per vessel	<0.01 *	CPUE	0.03 *
Vessel length	<0.01 *	Distance to grounds	0.07	Distance to grounds	0.06
Distance to grounds	0.14	Average speed	0.27	SFC	0.12
Pots per vessel	0.26	Fishing capacity	0.62	Fishing capacity	0.28
SFC	0.35	SFC	0.65	Pots per vessel	0.32
Importance of fuel	0.45	Importance of fuel	0.69	Efficiency (L/hr)	0.66
Days per trip	0.70	Vessel length	0.82	Days per trip	0.67
Efficiency (L/hr)	0.95	Engine HP	0.95	Importance of fuel	0.87

[a]P values for significant variables are displayed from the final multiple regression model. Insignificant variables were removed sequentially until all remaining values were significant, and P values for insignificant variables are displayed from the latest model before the variable was removed.

Table 5.5. Multiple regression analysis of variables significantly related to fuel use intensity in rock lobster fishing trips. Regression results are based on log-transformed FUI. Odds ratios display the predicted nominal change in FUI values, relative to 1, per change in input variable, with 95% confidence interval range.

		All trips				
Variable	**Units**	**Regression results**		**Odds ratios**		
		Estimate	Std. error	Estimate	95% conf. int.	
(Intercept)		2.879	0.120			
CPUE	kg/potlift	-0.220	0.031	0.802	0.754	0.854
Engine HP	10 HP	0.006	0.001	1.006	1.004	1.007
Fishing capacity	vessels/10t	0.009	0.003	1.009	1.004	1.014
Vessel length	m	0.020	0.007	1.020	1.006	1.035
		Single day trips				
Variable	Units	Regression results		Odds ratios		
		Estimate	Std. error	Estimate	95% conf. int.	
(Intercept)		3.553	0.075			
CPUE	kg/potlift	-0.251	0.043	0.778	0.713	0.850
Efficiency	L/hr	0.005	0.001	1.005	1.003	1.008
Pots per vessel	# pots	-0.002	0.000	0.998	0.997	0.999
		Multiday trips				
Variable	Units	Regression results		Odds ratios		
		Estimate	Std. error	Estimate	95% conf. int.	
(Intercept)		2.928	0.137			
Engine HP	10 HP	0.006	0.001	1.006	1.004	1.009
Vessel length	m	0.027	0.011	1.027	1.004	1.051
CPUE	kg/potlift	-0.233	0.099	0.792	0.641	0.979

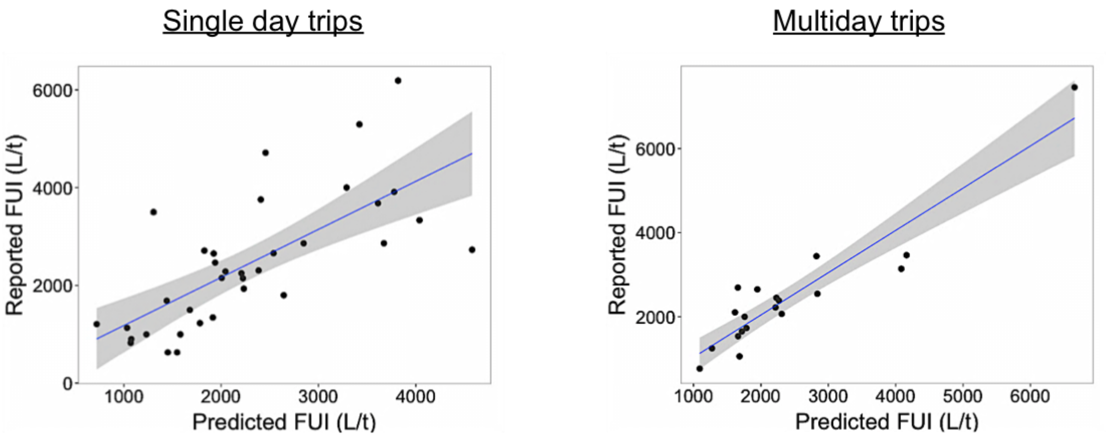

Figure 5.5. Model fit for single day and multiday lobster fishing trips, using factors with significant relationships to FUI identified in multiple regression models. Shaded area shows 95% confidence intervals. Single day trip model is based on relationships of FUI with CPUE (kg/potlift), engine efficiency (L/hr), and number of pots per vessel. Multiday trip model is based on relationships of FUI with engine HP, vessel length, and CPUE (kg/potlift).

5.5 Discussion

5.5.1 Comparison to other fisheries

The average FUI of landed rock lobster, caught using traps in Australia and New Zealand and weighted by regional production, was 1,890 L/t, placing the industry amongst the most fuel-intensive fisheries both regionally and globally (Figure 5.6). Other lobster fisheries around the world have also reported high levels of fuel consumption, owing primarily to their low catch rates when compared to fisheries targeting schooling fish. Estimates of FUI in other lobster fishing fleets include 990 L/t and 1,030 L/t for American lobster (*Homarus americanus*) caught with traps in the United States and Canada (Driscoll *et al.*, 2015); 2,160 L/t and 4,120 L/t for Norway lobster (*Nephrops norvegicus*) caught with traps and trawls, respectively (Ziegler and Valentinsson, 2008); and between 1,000 and 2,900 L/t for Tropical rock lobster caught by divers in the Torres Strait, Australia (van Putten *et al.*, *in press*).

Globally, average fuel inputs to marine capture fisheries have been estimated at 620 and 490 L/t, less than one-third of the consumption of rock lobster vessels (Parker *et al.*, in prep; Tyedmers *et al.*, 2005). The most intensive fisheries both regionally and globally typically target crustaceans, although high volumes of fuel are also consumed by some fisheries for flatfish and large pelagic species. The most fuel-efficient fisheries are those targeting small pelagic species, which typically consume less than one-tenth of the fuel required to land rock lobster. The Australian sardine (*Sardinops sagax*) fishery, for example, burns 92 L/t using purse seine gear to harvest large volumes of schooling fish (Figure 5.6).

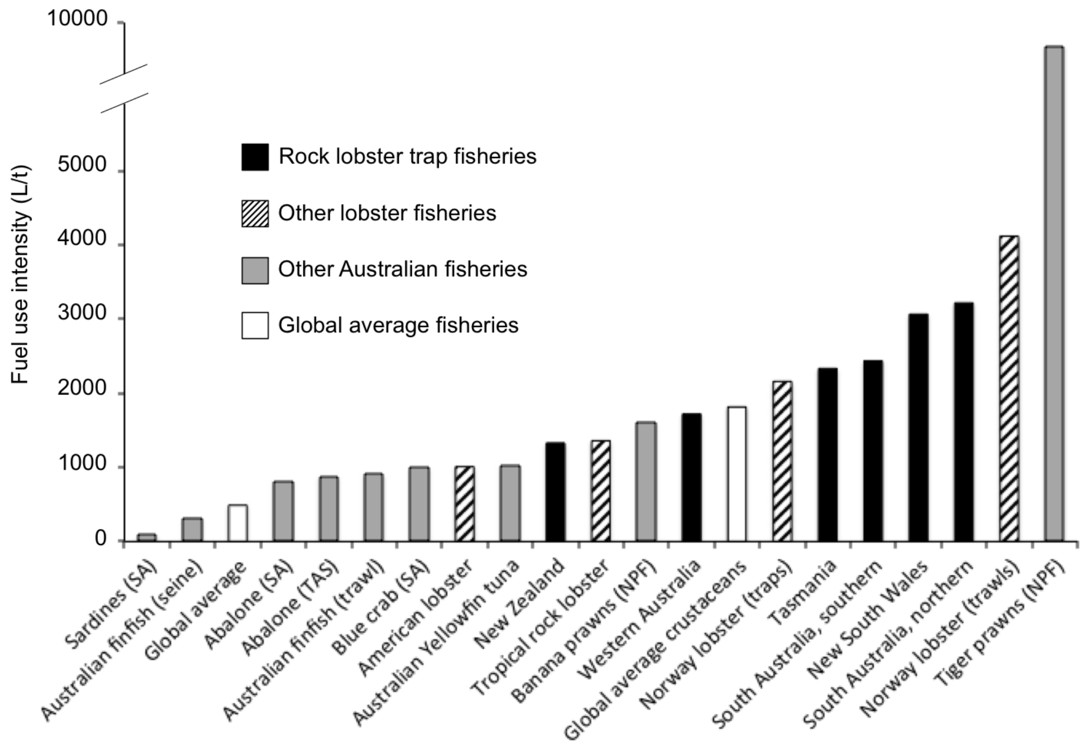

Figure 5.6. Fuel use intensity of Australian and New Zealand rock lobster trap fisheries compared to other lobster fisheries around the world, non-lobster fisheries in Australia, and the global average fishery FUI. SA = South Australia, TAS = Tasmania, NPF = Northern Prawn Fishery. Data relating to rock lobster fisheries from the current study. Data relating to other Australian fisheries from Parker *et al.* (2015a). Data relating to other lobster fisheries from Driscoll *et al.* (2015); van Putten *et al.* (*in press*); Ziegler and Valentinsson (2008). Data relating to global fisheries from Parker *et al.* (in prep); Tyedmers *et al.* (2005).

5.5.2 Technological drivers of fuel use

Technological characteristics of rock lobster fisheries varied markedly between regions. Average engine HP and fuel use per hour in Western Australia, for example, were 2.6 and 4.3 times that of Tasmanian vessels, respectively. Technological factors were found to influence the energy performance of rock lobster vessels here, but to varying degrees in different sectors. Engine HP and vessel length were both found to be significant drivers of FUI in multiday trips, but were less influential in single day trips. This may reflect the longer distance and time spent travelling in multiday trips, providing a longer window for technological efficiency measures to have an effect independently of other conditions.

Innovations in engine efficiency and vessel design have received a lot of attention in the literature and are often suggested as ideal options for reducing long-term energy costs in fisheries (Basurko *et al.*, 2013; Sterling and Goldsworthy, 2007; Wilson, 1999). However, evidence of relationships between fuel use and vessel size, engine HP, and other technological factors varies considerably between studies. Vessel size in European fisheries, for example, is positively correlated with fuel efficiency in demersal and pelagic trawlers, but negatively correlated with efficiency in beam trawlers and dredgers (Guillen *et al., in press*). Similarly, Ziegler and Hornborg (2014) found a relationship between vessel size and fuel use in lobster fisheries in Sweden, but no relationship in fisheries for shrimp or cod, and demonstrated that the relationships vary year to year. The variable influence of vessel size in fisheries also extends to comparisons between fleets: differences in target species and gear type influence fuel use much more than technological characteristics of individual vessels. Very large tuna purse seiners, for example, are relatively energy-efficient when compared with other fisheries with smaller vessels, and display no significant correlation between size and efficiency within the industry (Parker *et al.*, 2015b). Large factory processing trawlers have also been measured amongst the more efficient fishing vessels in some cases, in cases where they target a species with a highly localized biomass and schooling behaviour (Fulton, 2010; Parker and Tyedmers, 2013). Larger, more powerful vessels undoubtedly require more energy to operate; however, if catch rates benefit from economies of scale or better ability to travel to optimal fishing grounds, the increased energetic effort may actually lead to lower energy intensity.

Vessels whose energy consumption is linked more closely with gear operation, such as trawlers or dredgers, may benefit more from technological design improvements than vessels operating passive gears like traps. Optimizations in the size and design of otter boards, cables, and net mesh, for example, have been found to significantly reduce fuel consumption rates in some trawling fisheries by up to 40% (Khaled *et al.*, 2013; Parente *et al.*, 2008; Priour, 2009; Sterling and Goldsworthy, 2007). The influence of trip type in the relative role of technological factors in rock lobster energy performance suggests that vessels travelling great distances or fishing for long periods of time may also benefit more from design improvement, even if they are operating passive gears.

5.5.3 Behavioural drivers of fuel use

Behavioural adaptations are regularly suggested as cost-effective means to directly improve efficiency and manage rising fuel prices. However, our findings do not suggest that individual fishing behaviour has a substantial effect on the efficiency of rock lobster fisheries. In fact, those fishers that reported changes to their operations—either technological or behavioural—in response to high fuel costs actually performed worse than fishers that did not report any changes. There was a pattern of more fuel-intensive vessels reporting a higher importance of fuel costs. However, reported importance of fuel was not a significant predictor of FUI; rather, the greater importance attributed to fuel was likely in response to high fuel costs, rather than an indication of adaptive behavioural changes.

Numerous behavioural factors have been investigated in the literature, including vessel speed and decisions regarding when and where to fish. Because of the ease with which these behavioural changes can be made, many fishers are likely to rely on them for short-term adaptations (Abernethy *et al.*, 2010; Beare and Machiels, 2012). Reducing vessel speed, for example, has been shown to decrease trip fuel consumption in trawlers by between 10 and 50% (Basurko *et al.*, 2013; Latorre, 2001; Poos *et al.*, 2013). Speed may have a particularly strong impact on fisheries which travel greater distances, with relatively small reductions in speed associated with dramatic improvement in fuel use during the steaming phase of fishing trips (Parente *et al.*, 2008; Thomas *et al.*, 2010). However, our results did not find any significant relationship between average trip speed and FUI. Importantly, this study assessed average speed across the entire trip, and a more specific investigation of speeds during different portions of a fishing trip, such as steaming to fishing grounds, may identify opportunities to decrease fuel use.

A less measurable behavioural factor referred to as the “skipper effect” reflects the overall experience of fishers, and includes decisions such as where to locate stocks or how to respond to environmental conditions (Ruttan and Tyedmers, 2007; Vázquez-Rowe and Tyedmers, 2013). Abernethy *et al.* (2010), for example, reported that the most common responses of skippers to rising fuel costs included closer examination of catch by the skipper, more careful use of the tide for travel, and the choice not to fish during poor weather days. Skipper effect may explain some differences in FUI between similar vessels operating in the same region in this study, and data relating to skipper experience, such as number of years fishing, may be useful in future studies to try to incorporate this factor.

5.5.4 Managerial drivers of fuel use

CPUE was found here to be the only factor consistently influencing the FUI of rock lobster fishing vessels. Not only was it found to relate significantly to FUI of both single day and multiday fishing trips, but was also highest in the two regions that demonstrated the most energy efficient operations: New Zealand and Western Australia. Similar to the single day results presented here, Ziegler and Hornborg (2014) identified increases in biomass as a result of management as more influential to fuel consumption in Swedish fisheries than technological factors such as vessel size. Management decisions to limit fishing capacity, particularly by reducing the number of active vessels has been shown to have a compounded effect by both reducing inefficient "race to fish" behaviour, and by removing the least efficient vessels from the fishery.

Management regulations of fisheries can also influence energy performance directly. Driscoll and Tyedmers (2010) demonstrated the dramatic reduction on fuel use resulting from gear restriction in the New England Atlantic herring

(*Clupea harengus*) fishery which replaced trawls with purse seine gear with lower associated FUI. Farmery *et al.* (2014) modeled reduction in potential fuel consumption in rock lobster fisheries by changing fishing limits from maximum sustainable yield to maximum economic yield, and increasing or removing the limit on pot numbers. In the southern zone rock lobster fishery of South Australia, a boat buyback scheme was introduced in 1987, which resulted in the removal of 45 fishing licenses and over 2,400 pots, and led to a dramatic increase in CPUE between 1987 and 2002 (Sloan and Crosthwaite, 2007). While fuel use data are not available for most of that period, the relationship between FUI and CPUE would suggest that that management decision would have resulted in improved fuel use rates. A similar improvement in CPUE and fuel use – up to 50% reduction – has been documented in the northern prawn fishery of Australia after the implementation of a boat buyback in that fishery (Parker *et al.*, 2015a; Pascoe *et al.*, 2012).

Because rock lobster fisheries target a non-schooling species with a relatively low biomass compared to finfish, it is unlikely that the FUI of rock lobster fisheries could, at a sector-wide scale, reach the levels of efficiency achieved by other fisheries. North American lobster fisheries, for example, experience much higher catch rates per trip than rock lobster fisheries, and still burn much more fuel than most finfish fisheries (Driscoll *et al.*, 2015). However, the range in FUI between fisheries with varying rates of CPUE found here, coupled with evidence of fuel use responding to management changes both theoretically and in practice, suggests that there is substantial room for rock lobster fisheries to improve their performance via management.

5.6 Conclusions

Rock lobster fishers identify fuel costs as an important factor in their business, despite the relatively low role that fuel plays in the overall costs of rock lobster fisheries when compared with other fisheries in the Australia (Parker *et al.*, 2015a). Many fishers have already implemented technological or behavioural changes to their fishing operations. However, the effect of these changes may be outweighed by natural variation in catchability of rock lobster, and more durable improvement may come from focusing on catch rates rather than engine power and vessel design. In order to understand the effect of implemented changes fully, however, a longitudinal study tracking fuel performance, technological and behavioural changes, and biomass estimates would be required.

Rock lobster fisheries are unique compared to many other Australian and global fisheries, including other fisheries for lobster species, in the economic value of their product. Beach prices of US$50-100 far exceed, for example, those achieved in American lobster fisheries, due to the extraordinarily high demand for rock lobster in the Chinese market and a relatively low supply capacity. As a result, the cost of fuel is less likely to dramatically affect fishers' decision-making than it would in a fishery where prices were lower relative to fuel costs. Rock lobster fishermen are more likely to base their decisions whether to fish, where to fish, and how to fish, on the beach price rather than on the price of fuel.

If the future of fisheries includes higher energy costs, potential pricing of carbon emissions, and increased demand to provide low-carbon products to consumers, it would be prudent for the industry to seek options to improve energy performance now. Results here suggest that a combination of technological and managerial factors influence the fuel performance of rock lobster vessels. Management efforts targeted at rebuilding stocks and identifying optimal levels of effort—sector-wide and by individual vessels—are likely to achieve the most effective results across the industry, with the added benefit of improving ecological sustainability of fishing stocks.

Chapter 6. General discussion

The central goals of this thesis were to provide an overview of the magnitude and implications of fuel consumption in marine wild capture fisheries, and to analyze how and why fuel consumption and GHG emissions vary between vessels, fleets, and national fishing industries. To this end, research was undertaken at three scales. In Chapter Two, I explored fuel use at a global scale using a metaanalysis of all available primary and secondary data compiled in FEUD, and compared the efficiency of fisheries on the basis of L/t according to target species, gear, and location. Subsequently in Chapter Three, I combined fuel use data from Chapter Two with a global landings database to produce national and global estimates of GHG emissions. In Chapter Four, I explored the regional scale by calculating fuel consumption and fuel costs across a range of fisheries in Australia and compared fisheries targeting different species, employing different gears, and operating in different locations. Regional analysis tracked inputs to Australian fisheries over two decades to identify trends in fuel consumption and connections between efficiency, operating costs, and management changes. Finally, in Chapter Five, I explored the local scale by measuring FUI of individual rock lobster fishing boats in numerous locations in Australia and New Zealand and assessed the micro-level drivers of fuel use, including technological, behavioural, and managerial variables. In this chapter, I will briefly summarize the main themes arising from the collective work undertaken, discuss the environmental and socio-economic implications of fuel use at multiple scales, and posit future research directions.

6.1 Overview of key findings

Fisheries varied markedly in FUI and resulting GHG emissions at all scales. In Chapter Two, FUI records in FEUD ranged from as low as 10 L/t in surrounding net fisheries for small pelagics in Latin America (primarily targeting Peruvian anchovy), to over 4,000 L/t in bottom trawl crustacean fisheries in Oceania (primarily targeting prawns in Australia). This substantial variation in efficiency was reflected regionally when comparing Australian fisheries: FUI ranged from 92 L/t in the South Australian sardine fishery to 9,700 L/t in the Tiger prawn season of the Northern Prawn Fishery. This range reflects the varied nature of fisheries, which target thousands of species with very different behaviours, employ a wide range of unique fishing gears, and operate in diverse environments around the world.

The dramatic variation in efficiency between fleets was not surprising, as previous studies have identified a similar range. Inputs to Norwegian fisheries in 2001–2004 ranged from 106 L/t in small pelagic fisheries to 2,900 L/t in fisheries targeting Dover sole (*Solea solea*) (Schau *et al.*, 2009). FUI of North Atlantic fisheries in the late 1990s was as low as 20 L/t in Canadian fisheries for Atlantic herring, and as high as 2,700 L/t in German trawl fisheries for cod and flatfish (Tyedmers, 2001). Even within fisheries targeting similar species, FUI varies markedly between fisheries depending on gear type and individual species behaviour: for example, purse seine fisheries for skipjack and yellowfin tuna consume only one-tenth the fuel required by bluefin tuna hook and line fisheries (Tyedmers and Parker, 2012).

Generalizing marine fisheries as a single source when comparing production systems fails to recognize the vast variation between fisheries and leads to oversimplified, misleading conclusions. Fisheries are often treated as homogenous production systems or as a small subset of systems when comparing them to other forms of production. For example, in a recent assessment of the GHG implications of food choices and diets, fisheries were either classified as “trawl fisheries” or “non-trawl fisheries” (Tilman and Clark, 2014). As presented in Table 2.2 (page 29), both trawl fisheries and non-trawl fisheries can operate with FUIs from less than 100 L/t to more than 1,000 L/t. Assessments and comparisons of food systems, environmental declarations, and dietary recommendations for minimizing impact, would all be improved by recognizing and including the variation identified here both globally and regionally.

The most fuel-efficient fisheries globally and within Australia targeted small pelagic species. Eight of the ten most efficient fishery groupings in Chapter Two targeted small pelagics, while the two most efficient fisheries identified in Australia were the only two small pelagic fisheries assessed in Chapter Four. Small pelagic fisheries made up 21% of global landings and 2% of global fishery GHG emissions in 2011. The national fishing fleets of Chile and Peru, which included high landings of Peruvian anchovy, were estimated in Chapter Three to be the most efficient fleets in the world. Similarly, large fisheries for Gulf menhaden and Atlantic menhaden resulted in a low overall FUI and GHG intensity of the United States fleet.

When compared to other animal protein sources (Figure 2.2, page 40), small pelagic fish had a remarkably low GHG impact. The fact that fisheries for small pelagic species accounted for such a small portion of the GHG emissions in global fisheries, despite making up over one-fifth of landings, is important when considering how to maximize protein production with minimal impact. Small pelagic fish are highly nutritious, providing relatively high energy density and levels of omega-3 fatty acids (Domingo *et al.*, 2007; Gall and Kern, 2015), and make up an important component of the diet of many fishing communities in poor countries (Tacon and Metian, 2009). However, most small pelagic fishery landings are directed to livestock and aquaculture feeds rather than to human consumption (Tacon and Metian, 2009; FAO, 2013c). This means that a highly efficient source of protein is potentially lost to intermediate products in the supply chains of less efficient systems.

Crustacean fisheries were the most fuel- and GHG-intensive fisheries both globally and within Australia. Five of the ten most intensive fishery groupings globally in Chapter Two targeted crustaceans, while seven of the most intensive Australian fisheries assessed in Chapter Four targeted crustaceans. Crustacean fisheries made up 6% of global landings in 2011, but because of their high FUI they accounted for 24% of global fishery GHG emissions.

Identifying opportunities to reduce fuel consumption in crustacean fisheries is particularly important, given the relative impact improvements could have on the emissions of the global fishing industry. Consequently, in Chapter Five, I assessed the drivers of fuel use in rock lobster fisheries—one of the most intensive sectors of the Australian fishing industry. Even the most fuel-efficient sector of the rock lobster fishery (vessels in New Zealand) had an average FUI higher than every Australian non-crustacean fishery assessed in Chapter Four, with the exception of the 2002 southern/western longline tuna fishery. Reducing fuel consumption in the rock lobster fishing industry could have dramatic environmental and economic implications: if all rock lobster vessels had the same FUI as those in New Zealand, the industry would reduce their emissions by 30%, saving 7.5 million litres of fuel and 23,000 tonnes of CO_2-eq GHG emissions. If similar savings could be achieved in crustacean fisheries around the world, the carbon footprint of the global fishing industry could be decreased by as much as 12 million tonnes CO_2-eq.

Improving energy performance, and thus increasing the economic resilience of fishing fleets to volatile oil prices while decreasing the environmental burden of the industry, requires the identification of those factors which most heavily influence FUI. Drivers of FUI in rock lobster fisheries were assessed in Chapter Five. Factors varied between single day trips and multiday trips, further demonstrating the difficulty of generalizing across the industry. Both managerial and technological factors were identified as significant contributors to FUI, although CPUE was the only factor found to be consistently significant across all sectors of the fishery. As discussed in Chapter Five, much of the literature regarding micro-level drivers of FUI, particularly the grey literature from industry and government, focuses on technological innovations (Sterling and Goldsworthy, 2007; Wilson, 1999). However, results here suggest that managerial strategies may be more effective, and that the approach to improve fisheries energy performance should be tailored to each individual sector.

6.2 Climate change implications

Food production plays an unequivocal role in global GHG emissions (Garnett, 2008; Smith *et al.,* 2014; Steinfeld *et al.,* 2006), and dietary choices have a clear influence on the environmental impact of the food sector (Carlsson-Kanyama, 1998; Sonesson *et al.*, 2010; Tilman and Clark, 2014). It is necessary that the relative performance of different food systems and products be identified and communicated clearly to consumers and other stakeholders. Emissions from agriculture and livestock production receive much attention in the literature, while seafood is often excluded from assessments beyond individual LCAs, or is grossly generalized. Foley *et al.* (2011), for example, assessed the environmental impacts of global food production to feed a growing population, but did not consider fisheries. Similarly, a recent report on dietary influences on emissions by Wellesley *et al.* (2015) examined the GHG implications of increased meat production and meat-heavy diets, but did not discuss the relative impact of seafood or present any indication of emissions from fisheries. Even the reports from the Intergovernmental Panel on Climate Change include very little consideration of the fishing industry, providing a small amount of general information within a larger discussion of agriculture (Smith *et al.*, 2014). By synthesizing the large breadth of data from energy use studies and LCAs and producing scaled up global estimates of GHG emissions from the fishing industry, this thesis allows for accessible estimates to informs assessments of the industry relative to wider food production systems, alternative animal protein sources, and emission reduction goals.

When weighted by global volume of landings, landed fish in 2011 had a carbon footprint of 2.1 kg CO_2-eq per kg. Emissions from fisheries at the point of landing are similar to reported emissions from production of farmed salmonids and chicken, and lower than those from production of beef and pork (Figure 2.2, page 40). Fisheries have previously been reported as low-impact in terms of both GHG emissions (Sonesson *et al.*, 2010) and relative energy return on investment (Tyedmers and Parker, 2012; Tyedmers *et al.*, 2005). In Chapter Three, I demonstrated that fisheries contributed relatively little towards the total emissions of global food production. This does not equate to an insignificant finding, but rather it indicates that the industry as a whole is a relatively low-carbon source of animal protein, and that large sectors of the industry have the potential to produce protein far more efficiently than other sources and should be recognized for their low impact. While fisheries on average contribute relatively little to climate change, the variation in fuel use and GHG emissions between fleets means that certain fisheries and their resulting products are as carbon-intensive as beef and lamb production. This is particularly evident in Australia, where a relatively large portion of GVP comes from crustacean fisheries (Parker *et al.*, 2015a).

I tracked trends in global GHG emissions over two decades in Chapter Three, and found an increase in total emissions by just under 30% between 1990 and 2011. While this still accounts for a small percentage of global emissions, it is important in the context that fisheries—like all food production systems—need to reduce their GHG intensity, and clearly any efforts to achieve this have not been successful on a global scale. The modest decreases observed in some fleets in recent years have been outweighed by higher production from carbon-intensive fisheries. Failures of the industry to contribute to national and global emission reduction efforts could overshadow the low-carbon image that many fish products achieve when compared to other sources of animal protein.

Importantly, the research here only followed fisheries to the point of landing. This was done because of the recognized importance of the fishing stage in terms of energy and GHG emissions, and the prospect of using fuel as a proxy for GHGs. More complete assessments of GHG emissions from individual fisheries and their products are achieved using LCA, and are particularly important for those circumstances where fuel is not the primary driver of GHGs: when products are sourced from low-input fisheries (Buchspies *et al.*, 2011), include high-impact added ingredients (Svanes *et al.*, 2011), are packaged in intensive materials such as aluminum cans (Hospido *et al.*, 2006), or are transported by air (van Putten *et al.*, in press). There is particular need for LCA work to be carried out in seafood supply chains in developing countries, where both fuel use and emissions data are lacking, and where a large portion of global production occurs. In addition, further exploration of waste along seafood supply chains as a driver of inefficiency (Gustavsson *et al.*, 2011), as well as variable impacts from cooking and preparation of fish, is needed. Broad-scale data on seafood waste and product transport, combined with emissions from fuel use presented here, could produce reasonable estimates of fishery product GHGs up to the point of sale, and thus provide a useful indicator of environmental impact to consumers.

The contribution of this thesis to the understanding of GHG emissions from global food production pertains only to wild-capture fisheries. Aquaculture was excluded from all analyses. Aquaculture production systems are expected to be the source of any substantial increase in global seafood production, as most commercially viable capture fisheries are fully exploited and global output has not grown in the past two decades (FAO, 2013). Similar to fisheries, a large volume of work has been undertaken to measure and characterize the GHG emissions of culture systems (Henriksson *et al.*, 2013). The focus of this work has largely been on production of Atlantic salmon and Rainbow trout, and—as with fisheries—has been undertaken largely in Europe and North America (Ayer and Tyedmers, 2009; Aubin *et al.*, 2009;

Grönroos *et al.*, 2006; Pelletier *et al.*, 2009). There is a need for future research to scale this work up to the global industry and come to conclusions as to the role the aquaculture industry plays in feeding a growing global population sustainably. In particular, what are the GHG implications of the doubling of aquaculture production suggested by Waite *et al.* (2014) to meet the global demand for fish in 2050? With the established understanding of GHG emissions from livestock production, research on emissions from global aquaculture production combined with the research undertaken here on fisheries would together produce a much more complete picture of the contribution of animal protein production to climate change.

6.3 Food security implications

Potential effects of high fuel costs on the viability of local fisheries could impact food security, incomes, and the future of coastal communities in developing countries. As Pelletier and colleagues (2014) demonstrated, many poor countries are the most vulnerable to this, due to their reliance on fisheries as a source of food and income and their relatively low adaptive capacity compared to richer nations. This vulnerability will be of growing importance in areas where fishing fleets are transitioning from non-motorized to motorized vessels (Boopendranath and Hameed, 2013; Vivekenanden *et al.*, 2013). Developing country fleets are already disporportionately affected by fuel costs, which account for a larger portion of operating costs than in industrialized fleets (FAO, 2007); this is likely to be partly the results of lower labour costs. In Chapter Two, I discussed the stark lack of data from developing countries, with some exceptions; this was previously found by Tyedmers *et al.* (2005) in their assessment of global fuel use data a decade ago. In particular, very little data from China and southeast Asia are available even though those regions account for a large portion of global landings. Those studies that have been undertaken in the region (Hua and Wu, 2011; Park *et al.*, 2015) are from industrialized countries.

Clearly, much more work is needed on measuring and characterizing the energy performance of fishing fleets in the developing world, in order to understand the socio-economic implications of rising energy costs and modernization of fleets. Studies such as that undertaken in Chapter Five could provide guidance on how to improve the resilience of fishing fleets in regions where fisheries are necessary for local food security. Solutions will need to be tailored to local sectors, as the drivers of energy performance vary between fleets. It can be expected, however, that implementing effective management systems to ensure high CPUE will be integral to efforts to improve resilience of fisheries in developing countries to high and volatile fuel costs.

6.4 Fisheries management implications

Throughout this thesis, I discussed the role of fisheries management in influencing fuel consumption and GHG emissions in fisheries. In Chapter Five, differences in CPUE not only explained the relative energy performance of rock lobster fisheries in different regions, but was also a significant driver of fuel use in all fishing trips. The influence of management decisions on the energy performance of fisheries has previously been identified both directly (Driscoll and Tyedmers, 2010) and indirectly (Hua and Wu, 2011; Ziegler and Hornborg, 2014). Efforts to decrease the GHG emissions of national fleets would likely be better served by improving CPUE through management efforts, than by investing in technological innovations in vessel design and engine efficiency.

In the case of rock lobster fisheries, substantial savings on fuel could potentially be obtained with improvements to management. The efficiency rates achieved in New Zealand, for example, are the result of successful efforts to increase CPUE, in some cases achieving greater than a 100% increase in kg/potlift between 2000 and 2015 (NRLMG, 2015). Lobster products from New Zealand are now associated with less effort, less fuel, and a smaller carbon footprint than their Australian counterparts.

Regionally, decreasing trends in some Australian fisheries were related to changes in fishing capacity or biomass. This was most evident in the Northern Prawn Fishery, as a result of reductions in overcapacity (Pascoe *et al.*, 2012). European and North Atlantic fisheries also experienced increased rates of consumption in the 1990s and some European fleets have either halted or reversed that trend in the past decade (Cheilari *et al.*, 2013; Tyedmers, 2001). Again, there is strong evidence in Europe that the drivers of improving energy performance in recent years are more related to management, particularly stock biomass and fishing capacity, than to technology or fishing behaviour (Guillen *et al.*, in press; Ziegler and Hornborg, 2014). There is also evidence that management-induced improvements in biomass in Taiwan after 2005 resulted in dramatic reduction in FUI (Hua and Wu, 2011). The inverse was observed in Korean fisheries, which increased their FUI in 2011–2013 as a result of lower catch rates.

Fuel use should be of concern to fisheries managers as it pertains directly to the profitability of fishers and fleets. The cost of fuel in Australian fisheries ranges from just 2% of revenue in abalone fisheries to nearly 50% in some prawn fisheries. Implementing management options designed to improve fuel performance either directly or indirectly will improve vulnerability of those fisheries with the highest costs. Fuel use should also be considered with regards to management decisions such as pot limits, fishing season length, and gear restrictions, which could potentially have dramatic effects on fishing efficiency (Driscoll and Tyedmers, 2010; Farmery *et al.*, 2014), and future research should track changes in FUI after such management changes are made in order to quantify their effect. Fuel use could also be a useful measure for fisheries managers to track local fishing effort and changes in response to management decisions: the relationship between fuel consumption and CPUE should be of particular interest, as fuel may provide an accessible, easily monitored indicator of changes in catchability.

6.5 Conclusion

Measuring and improving the energy performance and GHG emissions from all food production systems is a necessary component of global efforts to satisfy energy demands and mitigate climate change in the 21st century. Providing food to a global population expected to reach 10 billion by 2050, while remaining within the capacity of the planet to provide resources and assimilate wastes—including carbon—is amongst the largest environmental and social challenges of this century. Understanding the role of wild capture fisheries in this challenge requires assessment of fisheries and their environmental impacts at all scales, from individual vessels to fleets to national and global industries.

As such, fuel consumption is a useful indicator of sustainability in marine capture fisheries, both economically and environmentally. Fisheries vary markedly in their fuel use, fuel costs, and GHG emissions, reflecting the vast variation of fishing fleets targeting different species, employing different gears, and operating in different locations. Even within individual fishing fleets, energy performance of vessels varies significantly and can be influenced by technological, behavioural, and managerial factors. As a result, generalization of fisheries and fishery-derived products is difficult, and assessments of global and regional food production impacts should seek to capture more of this variation.

Climate change and energy price volatility will continue to influence the economic and regulatory environment for fisheries throughout the coming decades. The industry, as well as the economies and communities which depend on it, will need to adapt to the new realities of high oil prices and demand for low-emission products. The measurement and improvement of energy performance within the industry at all scales will be necessary to inform strategies to adapt to rising energy prices, demand for low-impact products, and carbon-related policies to mitigate climate change. As such, understanding energy use and GHG emissions in marine capture fisheries—globally, regionally, and locally—is necessary in ensuring the industry's sustainability, both environmentally and socio-economically.

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APPENDIX A. Species and gear groupings to characterize fuel inputs to global fisheries

Table A1. List of target species groups in FEUD and global landings database.

Target Group Number	Target Group Description	Number of species ion landings database[a]	Number of FEUD records
	Unknown species		48
1	Pelagic, <30 cm	63	100
2	Pelagic, 30–90 cm	92	164
3	Pelagic, >90 cm	52	87
4	Demersal, <30 cm	34	12
5	Demersal, 30–90 cm	164	32
6	Demersal, >90 cm	78	68
7	Bathypelagic, <30 cm	4	1
8	Bathypelagic, 30–90 cm	17	12
9	Bathypelagic, >90 cm	3	0
10	Bathydemersal, <30 cm	5	3
11	Bathydemersal, 30–90 cm	28	1
12	Bathydemersal, >90 cm	18	15
13	Benthopelagic, <30 cm	14	0
14	Benthopelagic, 30–90 cm	78	29
15	Benthopelagic, >90 cm	50	363
16	Reef-associated, <30 cm	166	4
17	Reef-associated, 30–90 cm	246	6
18	Reef-associated, >90 cm	71	3
19	Sharks <90 cm	9	0
20	Sharks >90 cm	56	9
21	Rays <90 cm	16	3
22	Rays >90cm	35	3
23	Flatfishes <90 cm	44	36
24	Flatfishes >90 cm	7	37
25	Cephalopods	20	85
26	Shrimps	57	238
27	Lobsters and crabs	77	126
28	Jellyfish	0	0
29	Demersal molluscs	133	109
30	Krill	2	3

[a]Where species was not known, higher taxonomic ranks were used to associated a fishery with a target group.

Table A2. List of gear classes in FEUD and global landings database.

Gear class	Number of FEUD records
Unknown gear	189
Bottom trawls	479
Midwater trawls	174
Mobile seines	30
Surrounding nets	199
Gillnets and entangling nets	114
Hooks and lines	266
Traps and lift nets	83
Dredges	62
Grappling and wounding	0
Other gear	23
Mixed gear	4

APPENDIX B. Country landings, fuel, and GHG results

Table B1. Landings and rates of non-motorized fishing by country, 2011.

Country	Landings	% of vessels non-motorized	% of landings non-motorized
Albania	2,977	10	7
Algeria	101,759	44	18
American Samoa	4,777	50	4
Angola	252,500	63	31
Anguilla	1,007	15	10
Antigua and Barbuda	2,300	15	14
Argentina	774,200	8	3
Australia	158,108	1	1
Bahamas	10,223	15	15
Bahrain	17,668	37	17
Bangladesh	546,333	50	43
Barbados	1,826	15	12
Belarus	2,629	20	11
Belgium	22,206	2	1
Belize	204,276	15	7
Benin	7,743	47	27
Brazil	554,345	47	21
British Virgin Islands	1,200	15	8
Brunei Darussalam	2,100	6	0
Bulgaria	8,145	10	6
Cabo Verde	22,500	11	4
Cambodia	85,000	52	12
Cameroon	65,000	26	21
Canada	777,393	0	0
Chile	3,059,193	7	2
China	13,349,672	35	20
China; Hong Kong SAR	170,720	17	9
China; Macao SAR	1,500	17	12
China; Taiwan Province of	903,737	2	1
Colombia	59,646	15	2
Comoros	24,890	93	43
Congo	39,843	57	21
Cook Islands	4,300	50	8
Costa Rica	19,498	15	6
Cote dIvoire	65,305	63	46
Croatia	70,499	10	2
Cuba	24,113	15	10
Cyprus	1,164	10	6
Democratic People's Republic of Korea	200,000	44	28
Democratic Republic of the Congo	6,000	82	30
Denmark	732,880	4	1
Djibouti	1,667	80	54
Dominican Republic	13,032	15	12
Ecuador	507,174	28	6
Egypt	122,303	85	50
El Salvador	51,926	15	0
Equatorial Guinea	6,115	44	24

(Table B1 cont.)

Country	Landings	% of vessels non-motorized	% of landings non-motorized
Estonia	74,220	20	4
Falkland Islands (Malvinas)	66,952	8	3
Faroe Islands	4,437	0	0
Fiji	38,380	50	29
Finland	116,903	20	6
France	415,453	1	0
French Guiana	3,901	15	1
French Polynesia	12,799	50	9
Gabon	21,457	57	46
Gambia	40,600	37	25
Georgia	26,470	37	1
Germany	204,956	3	1
Ghana	243,524	38	8
Greece	70,496	10	4
Greenland	158,585	2	1
Grenada	2,321	15	7
Guadeloupe	9,800	15	4
Guatemala	17,343	15	0
Guinea	97,000	54	42
Guinea-Bissau	6,600	54	40
Guyana	42,385	15	1
Haiti	15,920	15	1
Honduras	9,062	15	8
Iceland	1,133,065	2	1
India	3,234,120	44	27
Indonesia	5,295,443	41	23
Iran (Islamic Republic of)	822,174	48	38
Iraq	3,294	37	34
Ireland	213,859	0	0
Israel	3,506	2	1
Italy	212,722	15	7
Jamaica	14,700	15	5
Japan	3,715,785	3	2
Kenya	6,917	76	60
Kiribati	65,335	50	14
Kuwait	9,000	37	13
Latvia	209,690	48	13
Lebanon	3,541	37	24
Liberia	7,070	63	34
Libya	30,000	44	25
Lithuania	114,653	10	2
Madagascar	95,423	100	12
Malaysia	1,369,002	6	3
Maldives	120,836	47	12
Malta	1,920	10	3
Marshall Islands	93,244	50	10
Martinique	4,900	15	6
Mauritania	356,490	3	1
Mauritius	4,318	93	88
Mayotte	29,178	93	30
Mexico	1,429,044	15	5

(Table B1 cont.)

Country	Landings	% of vessels non-motorized	% of landings non-motorized
Micronesia (Federated States of)	36,114	50	8
Morocco	949,881	3	1
Mozambique	116,478	97	3
Myanmar	2,166,320	51	41
Namibia	411,140	51	17
Netherlands	350,062	2	0
New Caledonia	3,714	50	14
New Zealand	426,379	1	0
Nicaragua	29,949	15	6
Nigeria	334,205	77	42
Norway	2,298,920	2	1
Oman	317,132	25	13
Pakistan	331,858	51	28
Panama	155,678	5	1
Papua New Guinea	171,073	50	10
Peru	8,210,457	11	1
Philippines	2,166,799	59	28
Poland	171,715	3	1
Portugal	68,269	18	14
Puerto Rico	1,461	15	8
Qatar	25,970	37	27
Republic of Korea	1,718,298	3	1
Reunion	2,406	93	27
Russian Federation	3,002,671	20	6
Saint Helena; Ascension and Tristan da Cunha	1,302	33	12
Saint Kitts and Nevis	31,001	15	6
Saint Lucia	1,963	15	8
Saint Pierre and Miquelon	903	0	0
Saint Vincent and the Grenadines	43,434	15	6
Samoa	10,829	50	12
Sao Tome and Principe	3,614	44	33
Saudi Arabia	101,853	85	55
Senegal	391,405	19	6
Seychelles	75,307	47	11
Sierra Leone	185,000	89	67
Singapore	1,618	4	3
Solomon Islands	50,924	50	7
Somalia	29,800	81	3
South Africa	526,568	38	11
Spain	1,030,872	7	3
Sri Lanka	372,193	50	31
Suriname	33,800	15	0
Sweden	180,228	2	0
Syrian Arab Republic	2,200	37	25
Thailand	1,522,537	3	1
Togo	19,109	58	33
Tonga	2,001	50	26
Trinidad and Tobago	13,898	15	10
Tunisia	101,854	44	20

(Table B1 cont.)

Country	Landings	% of vessels non-motorized	% of landings non-motorized
Turkey	477,667	2	0
Turks and Caicos Islands	6,901	15	13
Tuvalu	8,308	50	9
Ukraine	173,360	78	41
United Arab Emirates	149,586	37	28
United Kingdom	580,312	0	0
United Republic of Tanzania	77,884	82	52
United States of America	5,195,728	3	1
United States Virgin Islands	807	15	12
Uruguay	88,047	15	5
Vanuatu	56,076	50	6
Venezuela	202,000	1	1
Viet Nam	2,300,000	18	4
Yemen	157,261	37	15

Table B2. Country fuel and GHG emissions results

Country	FUI (L/t)	Aggregate GHG emissions (thousand t)	% of food production emissions from fisheries
Albania	942	12	0
Algeria	451	193	2
American Samoa	1,225	24	84
Angola	508	552	7
Anguilla	869	4	100
Antigua and Barbuda	877	9	26
Argentina	801	2,571	2
Australia	1,189	778	1
Bahamas	1,745	77	79
Bahrain	3,283	241	77
Bangladesh	391	962	1
Barbados	561	4	10
Belarus	1,043	12	0
Belgium	1,864	171	1
Belize	183	157	36
Benin	360	12	0
Brazil	825	1,942	0
British Virgin Islands	801	4	34
Brunei Darussalam	822	7	5
Bulgaria	375	13	0
Cabo Verde	620	58	23
Cambodia	926	334	2
Cameroon	512	140	1
Canada	518	1,665	2
Chile	155	1,979	14

Table B2 (cont.)

Country	FUI (L/t)	Aggregate GHG emissions (thousand t)	% of food production emissions from fisheries
China	809	46,617	7
China; Hong Kong SAR	674	481	91
China; Macao SAR	922	6	66
China; Taiwan Province of	654	2,447	49
Colombia	415	103	0
Comoros	551	60	21
Congo	390	66	9
Cook Islands	1,095	20	60
Costa Rica	858	70	2
Cote dIvoire	344	101	NA
Croatia	178	52	1
Cuba	981	101	1
Cyprus	1,110	5	1
Democratic People's Republic of Korea	413	364	7
Democratic Republic of the Congo	453	12	0
Denmark	488	1,479	11
Djibouti	487	4	1
Dominican Republic	1,009	56	1
Ecuador	303	640	4
Egypt	659	366	1
El Salvador	515	110	4
Equatorial Guinea	273	7	34
Estonia	206	64	2
Falkland Islands (Malvinas)	658	183	55
Faroe Islands	590	11	4
Fiji	675	111	11
Finland	94	47	1
France	811	1,394	2
French Guiana	1,410	23	15
French Polynesia	946	51	58
Gabon	414	39	12
Gambia	582	100	10
Georgia	88	10	0
Germany	449	381	1
Ghana	327	333	6
Greece	723	212	2
Greenland	491	322	70
Grenada	1,092	11	42
Guadeloupe	836	34	18
Guatemala	611	44	1
Guinea	516	214	2
Guinea-Bissau	594	17	1
Guyana	1,519	266	11
Haiti	838	55	1
Honduras	1,518	58	1
Iceland	380	1,785	79
India	436	6,128	1
Indonesia	574	13,044	7

Table B2 (cont.)

Country	FUI (L/t)	Aggregate GHG emissions (thousand t)	% of food production emissions from fisheries
Iran (Islamic Republic of)	463	1,724	2
Iraq	505	7	0
Ireland	523	463	2
Israel	857	12	0
Italy	831	737	2
Jamaica	788	48	6
Japan	471	7,259	20
Kenya	396	13	0
Kiribati	487	135	95
Kuwait	1,265	47	11
Latvia	108	98	3
Lebanon	554	9	1
Liberia	620	19	4
Libya	484	62	1
Lithuania	133	63	1
Madagascar	843	345	2
Malaysia	692	3,937	20
Maldives	618	311	100
Malta	1,264	10	11
Marshall Islands	476	187	100
Martinique	309	6	14
Mauritania	230	341	4
Mauritius	182	6	3
Mayotte	713	89	100
Mexico	446	2,670	3
Micronesia (Federated States of)	596	90	85
Morocco	246	968	4
Mozambique	913	444	9
Myanmar	394	3,764	6
Namibia	250	447	9
Netherlands	581	841	3
New Caledonia	1,044	16	7
New Zealand	522	920	2
Nicaragua	919	116	1
Nigeria	580	855	2
Norway	323	3,073	37
Oman	622	830	40
Pakistan	723	1,037	1
Panama	396	255	7
Papua New Guinea	502	362	6
Peru	77	2,628	9
Philippines	427	4,033	7
Poland	179	128	0
Portugal	633	182	2
Puerto Rico	722	4	1
Qatar	689	77	6
Republic of Korea	566	4,030	16
Reunion	1,302	13	8
Russian Federation	241	3,038	3

Table B2 (cont.)

Country	FUI (L/t)	Aggregate GHG emissions (thousand t)	% of food production emissions from fisheries
Saint Helena; Ascension and Tristan da Cunha	773	4	86
Saint Kitts and Nevis	165	22	79
Saint Lucia	818	7	17
Saint Pierre and Miquelon	923	3	89
Saint Vincent and the Grenadines	201	36	69
Samoa	734	34	18
Sao Tome and Principe	459	7	35
Saudi Arabia	1,558	680	7
Senegal	306	501	6
Seychelles	949	298	98
Sierra Leone	351	292	11
Singapore	925	6	5
Solomon Islands	752	160	70
Somalia	793	99	0
South Africa	239	538	1
Spain	571	2,442	5
Sri Lanka	468	775	11
Suriname	1,153	161	13
Sweden	325	242	3
Syrian Arab Republic	515	5	0
Thailand	660	4,156	5
Togo	265	22	1
Tonga	861	8	10
Trinidad and Tobago	723	42	15
Tunisia	544	237	4
Turkey	244	483	1
Turks and Caicos Islands	574	17	100
Tuvalu	515	18	76
Ukraine	210	166	0
United Arab Emirates	628	410	21
United Kingdom	588	1,411	3
United Republic of Tanzania	504	184	0
United States of America	359	7,733	2
United States Virgin Islands	836	3	15
Uruguay	1,176	430	2
Vanuatu	487	114	22
Venezuela	572	479	2
Viet Nam	900	8,621	12
Yemen	675	447	4

APPENDIX C. Cost and revenue data and fuel use estimates for Australian fisheries

Table C1. Average operating costs of fishing in the Northern Prawn Fishery, 1993-2010. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1993	2,258	3,470	0	2,313
1994	2,528	4,615	0	3,340
1995	1,713	4,129	0	2,767
1996	1,666	3,250	0	2,805
1997	1,888	3,294	0	2,088
1998	1,621	3,616	0	2,114
1999	1,815	3,695	0	2,466
2000	2,915	4,965	0	3,884
2001	2,251	4,218	0	2,112
2002	2,387	3,914	0	2,487
2003	2,546	3,510	0	2,355
2004	2,647	2,920	0	1,955
2005	4,335	3,595	0	2,363
2006	5,386	3,511	0	2,003
2007	4,259	3,126	0	1,747
2008	3,124	2,655	0	1,251
2009	3,171	3,019	0	1,682
2010	2,547	3,168	0	1,715

Table C2. FUI and fuel costs relative to fishing revenues and costs in the Northern Prawn Fishery, 1993-2010.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1993	6433	17.6	28.1
1994	7787	14.8	24.1
1995	4456	11.2	19.9
1996	4328	13.0	21.6
1997	4650	15.7	26.0
1998	4416	12.1	22.1
1999	5605	13.0	22.8
2000	7073	15.2	24.8
2001	4209	13.3	26.2
2002	5099	15.5	27.2
2003	5875	17.8	30.3
2004	4812	22.5	35.2
2005	6804	34.2	42.1
2006	6501	39.9	49.4
2007	5244	34.3	46.6
2008	3173	29.0	44.4
2009	3748	28.0	40.3
2010	3474	21.4	34.3

Table C3. Average operating costs of fishing in the Torres Strait prawn fishery, 1993-2008. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1993	1,404	2,887	0	1,455
1994	1,590	3,481	0	2,243
1995	2,163	4,328	0	3,114
1996	2,097	4,269	0	2,771
1997	1,633	4,093	0	1,490
1998	1,421	4,292	0	1,792
1999	1,459	3,842	0	2,148
2000	2,342	4,983	0	2,206
2001	2,539	4,576	0	1,647
2002	2,546	4,071	0	2,023
2003	3,451	3,604	0	1,534
2004	3,147	2,946	0	1,267
2005	3,967	3,342	0	1,340
2006	4,155	2,858	0	1,646
2007	4,909	2,705	0	1,502
2008	4,766	3,224	0	1,245

Table C4. FUI and fuel costs relative to fishing revenues and costs in the Torres Strait prawn fishery, 1993-2008.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1993	4000	17.3	24.4
1994	4897	15.4	21.7
1995	5626	16.1	22.5
1996	5446	16.4	23.0
1997	4021	15.5	22.6
1998	3871	11.7	18.9
1999	4506	12.4	19.6
2000	5683	16.2	24.6
2001	4748	17.1	29.0
2002	5440	19.0	29.5
2003	7965	27.8	40.2
2004	5721	30.2	42.8
2005	6225	37.5	45.9
2006	5015	42.1	48.0
2007	6044	50.8	53.9
2008	4841	45.1	51.6

Table C5. Average operating costs of fishing in the Eastern tuna fishery, 1993-2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1993	570	1,581	165	817
1994	514	1,825	219	1,079
1995	536	2,026	170	1,227
1996	703	2,274	573	1,146
1997	577	2,163	543	1,354
1998	603	2,083	271	1,296
1999	494	2,405	309	1,346
2000	1,020	3,860	673	1,752
2001	1,176	3,415	495	1,392
2002	1,135	3,048	686	1,448
2003	1,430	2,610	648	1,523
2004	1,113	1,712	445	922
2005	1,201	1,733	520	813
2006	1,008	1,227	376	633
2007	808	1,063	228	640
2008	923	1,367	266	618
2009	872	1,761	277	831
2010	742	1,511	334	763
2011	851	1,678	334	742

Table C6. FUI and fuel costs relative to fishing revenues and costs in the Eastern tuna fishery, 1993-2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1993	1624	10.9	18.2
1994	1583	8.2	14.1
1995	1394	7.7	13.5
1996	1826	10.0	15.0
1997	1420	8.0	12.4
1998	1642	9.6	14.2
1999	1526	6.3	10.9
2000	2476	9.6	14.0
2001	2199	12.5	18.2
2002	2425	12.0	18.0
2003	3300	17.9	23.0
2004	2024	16.6	26.6
2005	1884	17.7	28.1
2006	1216	20.2	31.1
2007	994	19.1	29.5
2008	937	18.6	29.1
2009	1030	14.3	23.3
2010	1012	14.1	22.2
2011	1027	14.2	23.6

Table C7. Average operating costs of fishing in the Southeast finfish fishery, combined trawl and seine, 1993-2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1993	236	574	0	354
1994	304	570	0	334
1995	325	656	0	364
1996	368	643	0	364
1997	337	645	0	329
1998	378	741	0	447
1999	334	677	0	454
2000	478	723	0	558
2001	453	715	0	329
2002	493	801	0	393
2003	434	692	0	252
2004	431	608	0	241
2005	585	763	0	299
2006	528	615	0	169
2007	640	871	0	289
2008	687	827	0	242
2009	768	1,027	0	316
2010	610	1,315	0	428
2011	516	1,104	0	357

Table C8. FUI and fuel costs relative to fishing revenues and costs in the Southeast finfish fishery, combined trawl and seine, 1993-2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1993	672	10.3	20.3
1994	936	12.7	25.2
1995	845	14.3	24.2
1996	955	16.8	26.7
1997	831	15.7	25.7
1998	1029	15.3	24.1
1999	1030	15.6	22.8
2000	1160	20.2	27.2
2001	847	20.3	30.3
2002	1054	19.9	29.2
2003	1002	20.2	31.5
2004	783	22.2	33.6
2005	918	24.9	35.5
2006	638	24.1	40.3
2007	788	19.2	35.6
2008	697	22.5	39.1
2009	908	21.2	36.4
2010	832	15.4	25.9
2011	623	15.5	26.1

Table C9. Average operating costs of fishing in the Southeast finfish trawl fishery, 1993-2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1993	240	557	0	358
1994	312	557	0	338
1995	340	635	0	378
1996	390	623	0	377
1997	352	628	0	340
1998	396	719	0	465
1999	355	652	0	475
2000	512	700	0	586
2001	482	705	0	347
2002	528	788	0	417
2003				
2004	447	592	0	249
2005	616	737	0	312
2006				
2007				
2008	771	809	0	248
2009	869	960	0	336
2010	714	1,185	0	526
2011	597	999	0	431

Table C10. FUI and fuel costs relative to fishing revenues and costs in the Southeast finfish trawl fishery, 1993-2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1993	683	10.4	20.8
1994	960	13.0	25.8
1995	883	15.0	25.1
1996	1012	17.8	28.0
1997	867	16.4	26.7
1998	1080	16.0	25.1
1999	1095	16.6	23.9
2000	1242	21.7	28.5
2001	901	21.6	31.4
2002	1128	21.3	30.4
2003			
2004	812	23.0	34.7
2005	966	26.2	37.0
2006			
2007			
2008	784	25.3	42.2
2009	1028	24.0	40.2
2010	973	18.0	29.4
2011	720	18.0	29.5

Table C11. Average operating costs of fishing in the Southeast finfish seine fishery, 1993-2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1993	174	837	0	291
1994	161	804	0	253
1995	153	900	0	196
1996	138	859	0	224
1997	157	861	0	201
1998	157	1,003	0	224
1999	111	945	0	225
2000	109	979	0	252
2001	168	812	0	151
2002	203	909	0	183
2003				
2004	273	763	0	167
2005	307	996	0	187
2006				
2007				
2008	250	918	0	208
2009	243	1,375	0	215
2010	279	1,731	0	116
2011	234	1,470	0	100

Table C12. FUI and fuel costs relative to fishing revenues and costs in the Southeast finfish seine fishery, 1993-2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1993	496	7.6	13.4
1994	495	6.7	13.2
1995	398	6.7	12.2
1996	357	6.3	11.3
1997	387	7.3	12.9
1998	429	6.4	11.4
1999	343	5.2	8.7
2000	265	4.6	8.2
2001	314	7.5	14.8
2002	434	8.2	15.7
2003			
2004	497	14.1	22.7
2005	482	13.1	20.6
2006			
2007			
2008	254	8.2	18.2
2009	287	6.7	13.2
2010	380	7.0	13.1
2011	283	7.0	13.0

Table C13. Average operating costs of fishing in the Southern shark fishery, 1993-2001. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1993	257	1,093	11	513
1994	323	1,209	12	556
1995	153	1,418	2	337
1996	227	1,458	4	514
1997	268	1,497	1	562
1998	281	1,515	0	564
1999	438	2,263	0	646
2000	294	1,605	1	344
2001	295	1,826	1	362

Table C14. FUI and fuel costs relative to fishing revenues and costs in the Southern shark fishery, 1993-2001.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1993	733	9.6	13.7
1994	994	11.3	15.4
1995	397	5.1	8.0
1996	591	6.5	10.3
1997	661	7.4	11.5
1998	766	8.3	11.9
1999	1352	8.6	13.1
2000	714	8.4	13.1
2001	552	7.6	11.9

Table C15. Average operating costs of fishing in the South Australia abalone fishery, 1998-2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1998	507	9,238	9	948
1999	443	8,374	8	894
2000	606	10,766	8	839
2001	440	12,390	4	981
2002	445	12,010	4	1,039
2003	452	13,105	4	1,070
2004	454	12,590	4	1,092
2005	530	8,874	11	1,321
2006	577	9,830	11	1,399
2007	593	10,061	11	1,453
2008	576	9,703	4	819
2009	664	10,804	5	966
2010	621	9,151	4	928
2011	660	9,564	9	1,003

Table C16. FUI and fuel costs relative to fishing revenues and costs in the South Australia abalone fishery, 1998-2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1998	1381	1.5	4.7
1999	1369	1.5	4.6
2000	1472	1.7	5.0
2001	823	1.0	3.2
2002	951	1.1	3.3
2003	1044	1.1	3.1
2004	826	1.3	3.2
2005	831	1.4	4.9
2006	696	1.5	4.9
2007	731	1.7	4.9
2008	585	1.7	5.2
2009	784	1.7	5.3
2010	847	1.9	5.8
2011	796	1.9	5.9

Table C17. Average operating costs of fishing in the South Australia blue crab fishery, 1998-2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1998	458	1,947	143	366
1999	397	1,937	138	360
2000	469	1,766	112	292
2001	613	2,535	139	354
2002	575	2,953	136	346
2003	562	3,058	139	361
2004	518	3,008	133	349
2005	1,028	1,672	115	931
2006	1,037	2,056	109	908
2007	943	2,342	105	837
2008	1,098	2,129	112	912
2009	906	1,956	104	788
2010	793	1,991	123	759
2011	701	2,560	118	239

Table C18. FUI and fuel costs relative to fishing revenues and costs in the South Australia blue crab fishery, 1998-2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1998	1247	9.9	15.7
1999	1225	8.9	14.0
2000	1137	12.0	17.8
2001	1145	11.1	16.8
2002	1229	9.3	14.3
2003	1296	9.2	13.6
2004	941	8.7	12.9
2005	1614	14.7	27.4
2006	1252	12.9	25.2
2007	1161	10.7	22.3
2008	1115	12.5	25.8
2009	1071	11.6	24.1
2010	1082	10.7	21.6
2011	846	7.8	19.4

Table C19. Average operating costs of fishing in the Gulf of St Vincent prawn fishery, 1998-2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1998	586	5,531	0	797
1999	410	5,362	0	599
2000	607	6,843	0	607
2001	627	6,285	0	622
2002	966	5,622	0	1,317
2003	1,500	5,605	0	2,065
2004	1,536	5,559	0	2,143
2005	1,712	5,752	0	987
2006	1,527	5,341	0	859
2007	1,206	5,100	0	681
2008	1,567	4,637	0	519
2009	1,214	4,816	0	413

Table C20. FUI and fuel costs relative to fishing revenues and costs in the Gulf of St Vincent prawn fishery, 1998-2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1998	1597	3.8	8.5
1999	1266	2.8	6.4
2000	1473	3.2	7.5
2001	1173	3.6	8.3
2002	2065	5.3	12.2
2003	3462	8.2	16.4
2004	2792	8.5	16.6
2005	2687	9.7	20.3
2006	1843	9.3	19.8
2007	1485	7.7	17.3
2008	1591	12.3	23.3
2009	1435	9.5	18.8

Table C21. Average operating costs of fishing in the Spencer Gulf and West Coast prawn fishery, 1998-2009. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1998	680	3,911	0	983
1999	647	4,906	0	1,005
2000	1,153	6,331	0	1,226
2001	906	6,246	0	797
2002	924	6,625	0	848
2003	1,291	7,103	0	1,200
2004	1,027	8,129	0	968
2005	1,441	5,289	0	1,235
2006	1,362	6,033	0	1,137
2007	1,295	6,791	0	1,084
2008	1,985	5,670	0	742
2009	2,256	6,006	0	867

Table C22. FUI and fuel costs relative to fishing revenues and costs in the Spencer Gulf and West Coast prawn fishery, 1998-2009.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1998	1853	5.8	12.2
1999	1996	4.5	9.9
2000	2798	6.4	13.2
2001	1694	5.1	11.4
2002	1974	5.1	11.0
2003	2979	6.9	13.5
2004	1866	5.0	10.1
2005	2261	8.8	18.1
2006	1644	7.6	16.0
2007	1594	6.7	14.1
2008	2016	12.6	23.6
2009	2667	14.0	24.7

Table C23. Average operating costs of fishing in the northern zone South Australia Rock lobster fishery, 1998-2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1998	1,990	9,503	1,117	1,951
1999	1,636	8,748	970	1,728
2000	2,584	10,190	1,024	1,863
2001	3,844	12,068	1,380	2,488
2002	4,258	14,161	1,326	2,869
2003	4,105	11,517	1,196	2,803
2004	5,113	8,678	1,520	3,538
2005	5,312	9,652	1,966	2,047
2006	4,984	12,449	1,746	1,866
2007	4,723	14,643	1,557	1,778
2008	5,369	11,476	1,752	2,953
2009	5,833	16,472	1,312	3,294
2010	4,378	17,399	612	2,541
2011	3,616	13,051	1,356	3,325

Table C24. FUI and fuel costs relative to fishing revenues and costs in the northern zone South Australia Rock lobster fishery, 1998-2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1998	5422	6.8	13.7
1999	5052	6.2	12.5
2000	6271	8.7	16.5
2001	7187	11.6	19.4
2002	9097	11.0	18.8
2003	9474	13.0	20.9
2004	9294	21.5	27.1
2005	8336	20.4	28.0
2006	6016	15.4	23.7
2007	5815	12.9	20.8
2008	5453	15.5	24.9
2009	6896	12.2	21.7
2010	5970	9.0	17.6
2011	4362	7.9	16.9

Table C25. Average operating costs of fishing in the southern zone South Australia Rock lobster fishery, 1998-2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
1998	1,664	11,097	1,020	1,975
1999	1,330	10,400	859	1,697
2000	1,496	11,575	644	1,309
2001	1,656	10,821	855	1,314
2002	1,908	18,359	853	1,590
2003	1,325	13,077	591	1,111
2004	1,491	9,769	684	1,272
2005	1,661	7,292	812	1,515
2006	1,979	9,178	953	1,759
2007	2,199	11,416	1,003	1,969
2008	3,321	10,946	1,581	2,262
2009	4,990	16,884	1,637	3,485
2010	6,145	16,256	688	4,405
2011	4,703	14,766	2,487	3,762

Table C26. FUI and fuel costs relative to fishing revenues and costs in the southern zone South Australia Rock lobster fishery, 1998-2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
1998	4532	5.5	10.6
1999	4106	4.8	9.3
2000	3631	5.0	10.0
2001	3096	5.2	11.3
2002	4077	5.0	8.4
2003	3058	3.7	8.2
2004	2710	5.7	11.3
2005	2607	5.8	14.7
2006	2388	5.7	14.3
2007	2707	5.3	13.3
2008	3373	8.1	18.3
2009	5899	8.2	18.5
2010	8379	10.8	22.3
2011	5672	8.7	18.3

Table C27. Average operating costs of fishing in the South Australia sardine fishery, 2002-2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
2002	41	243	5	78
2003	33	339	4	65
2004	28	281	3	55
2005	22	207	2	42
2006	99	228	1	45
2007	92	245	1	46
2008	95	221	1	47
2009	79	203	4	56
2010	72	203	4	53
2011	70	193	4	52

Table C28. FUI and fuel costs relative to fishing revenues and costs in the South Australia sardine fishery, 2002-2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
2002	87	5.8	11.1
2003	77	3.4	7.6
2004	51	3.4	7.6
2005	34	3.7	8.0
2006	119	17.6	26.5
2007	113	15.2	24.0
2008	96	17.3	26.1
2009	93	12.5	23.1
2010	99	11.5	21.8
2011	84	12.0	21.9

Table C29. Average operating costs of fishing in the Tasmanian Rock lobster fishery, 2011. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
2011	2,949	9,369	1,570	1,907

Table C30. FUI and fuel costs relative to fishing revenues and costs in the Tasmanian Rock lobster fishery, 2011.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
2011	3557	6.0	18.7

Table C31. Average operating costs of fishing in the southern and western tuna fishery, 2002. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
2002	930	2,045	662	929

Table C32. FUI and fuel costs relative to fishing revenues and costs in the southern and western tuna fishery, 2002.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
2002	1986	11.9	20.4

Table C33. Average operating costs of fishing in the Tasmanian small pelagic trawl fishery, 2004-2006. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
2004	78			
2005	106			
2006	151			

Table C34. FUI and fuel costs relative to fishing revenues and costs in the Tasmanian small pelagic trawl fishery, 2004-2006.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
2004	141	9.6	
2005	167	17.9	
2006	182	26.9	

Table C35. Average operating costs of fishing in the Tasmanian abalone fishery, 2012. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
2012	807	4,390	0	343

Table C36. FUI and fuel costs relative to fishing revenues and costs in the Tasmanian abalone fishery, 2012.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
2012	878	2.3	14.6

Table C37. Average operating costs of fishing in the New South Wales abalone fishery, 2002. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
2002	563	15,234	0	611

Table C38. FUI and fuel costs relative to fishing revenues and costs in the New South Wales abalone fishery, 2002.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
2002	1203	1.4	3.4

Table C39. Average operating costs of fishing in the New South Wales estuary general fishery, 2000. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
2000	226	3,235	28	116

Table C40. FUI and fuel costs relative to fishing revenues and costs in the New South Wales estuary general fishery, 2000.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
2000	549	6.2	6.3

Table C41. Average operating costs of fishing in the New South Wales ocean trap and line fishery, 2000. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
2000	543	2,077	267	394

Table C42. FUI and fuel costs relative to fishing revenues and costs in the New South Wales ocean trap and line fishery, 2000.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
2000	1319	11.1	16.6

Table C43. Average operating costs of fishing in the New South Wales ocean prawn fishery, 2000. Costs calculated per tonne of round weight landings.

Year	Fuel ($)	Labour ($)	Bait/ice ($)	Repairs ($)
2000	1,709	2,055	63	2,009

Table C44. FUI and fuel costs relative to fishing revenues and costs in the New South Wales ocean prawn fishery, 2000.

Year	FUI (L/t)	Fuel costs as % revenue	Fuel costs as % expenditures
2000	4147	15.8	29.3

APPENDIX D. Rock lobster fuel use fisher survey and cover letter

Measuring and characterizing fuel inputs and costs in Australian and New Zealand Rock lobster fisheries

Information for study participants

You are invited to participate in a research project aiming to assess the fuel performance of Rock lobster fisheries in Australia and New Zealand. This project is being carried out by Robert Parker in partial fulfillment of a PhD degree at the University of Tasmania under the supervision of Drs Klaas Hartmann, Caleb Gardner, Bridget Green and Reg Watson. The project is funded by Seafood CRC.

The purpose of the study is to measure rates of fuel use (litres per tonne) and fuel expenditure ($) of different fisheries targeting Rock lobster species, and to analyze fuel performance relative to a number of factors such as fishery structure, biomass, effort, and technology. To this end, the attached questionnaire has been formulated and circulated to Rock lobster fishers in Australia and New Zealand with the help of managers and industry groups. As an active fisher, you have been invited to participate by filling out this questionnaire and returning it using the included postage-paid envelope, by email to robert.parker@utas.edu.au, or by using the online survey.

Your participation in this survey is completely voluntary. You will not be identified in any publications of the research, and all information you provide will be kept confidential and aggregated for analysis.

Results of the analysis will be published in Mr. Parker's PhD thesis and will be provided to Rock lobster industry groups in the participating regions to be made available for those interested.

This study has been approved by the Tasmanian Social Sciences and Human Research Ethics Committee. If you have concerns or complaints about the conduct of this study, please contact the Executive Officer of the HREC (Tasmania) Network on (03) 6226 7479 or email human.ethics@utas.edu.au. The Executive Officer is the person nominated to received complaints from resarch participants. Please quote ethics reference number H0013670.

If you have any questions about the questionnaire or project, please contact Mr. Parker at the phone number or email below.

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Part 1: Vessel characteristics in 2012-2013 fishing year

Vessel length: _________ m

Engine type (select one): inboard / shaft / stern drive / jet / outboard

Vessel horsepower: _________ HP / kW

Vessel fuel efficiency at normal steaming speed: _________ L / hour

Vessel GRT: _________ t

Part 2: Catch and effort in 2012-2013 fishing year

Which fishery were you active in during the 2012-2013 fishing year? (select one)

____ Western Australia
____ South Australia (northern zone)
____ South Australia (southern zone)
____ Tasmania
____ New South Wales
____ New Zealand CRA 5
____ New Zealand CRA 8

Do you participate in fisheries for species other than lobster? If so, which ones? (NOTE: If you are active in multiple fisheries, please only include lobster fishery operations in the remainder of this questionnaire)

% of quota leased: _________ % (NZ total ACE)

Number of days actively fished in 2012-13 fishing year: _________ days

Number of pots: _________ pots

Number of potlifts in 2012-13 fishing year: _________

Landings of lobsters: Species: _____________ Catch: _________ kg
_____________ _________ kg

Total landings of species other than lobsters: _________ kg

Fuel expenditure: _________ $/year

Fuel consumption: _________ L/year

Type of fuel: _____ Petrol _____ Diesel

Part 3: Describing a typical trip

Trip length: __________ days or __________ hours

Distance travelled to fishing grounds: __________ km

Distance travelled per fishing day while at fishing grounds: __________ km

Average number of potlifts per day: __________

Average fuel use: __________ L/day or __________ L/trip

How is catch typically transported to port? (select one)
Fishing vessel / Another vessel / Helicopter

Average amount of bait used per day: __________ kg

Main species of bait: _________________________ , _________________________

Part 4: Role of fuel

Approximately what % of fishing costs is attributed to fuel? __________

How important would you say is the cost of fuel relative to other costs (labour, repairs, etc.) in your fishing operations? (select one)

___ VERY IMPORTANT
___ IMPORTANT
___ NEITHER IMPORTANT OR UNIMPORTANT
___ UNIMPORTANT
___ VERY UNIMPORTANT

Would you say that your fishing operations and/or fishing behaviour have changed in the past several years in response to the increased price of fuel? How so? (*e.g.* change in distance travelled to fishing grounds, change in steaming speed, change in number of days fishing, etc.)?

Do you expect the role of fuel to be more or less important to your fishing operations in the next five years? (select one)

___ MUCH MORE IMPORTANT
___ SLIGHTLY MORE IMPORTANT
___ NO CHANGE
___ SLIGHTLY LESS IMPORTANT
___ MUCH LESS IMPORTANT

Do you expect your fishing operations to change in response to the price of fuel in the next five years? How so?

Do you expect other factors (*e.g.* market prices, stock status) to change your fishing operations in coming years in ways that will affect your fuel use and fuel costs?

APPENDIX E. Copies of published articles

Parker, R.W.R., & Tyedmers, P.H. (2015). Fuel consumption of global fishing fleets: Current understanding and knowledge gaps. *Fish and Fisheries*, *16*(4), 684-696.

Parker, R.W.R., Hartmann, K., Green, B.S., Gardner, C., & Watson, R.A. (2015). Environmental and economic dimensions of fuel use in Australian fisheries. *Journal of Cleaner Production, 87*, 78-86.

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